Benthic TMDL Development for Bailey Creek, Nuttree Branch, Oldtown Creek, Proctors Creek, Rohoic Creek, and Swift Creek Watersheds Located in Chesterfield, Dinwiddie, and Prince George Counties and Cities of Hopewell, Colonial Heights, and Petersburg

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Acronyms

AllForX	All-Forest Load Multiplier
CADDIS	Causal Analysis Diagnosis Decision Information System
CBP	Chesapeake Bay Program
CREP	Conservation Reserve Enhancement Program
CV	Coefficient of Variation
EQIP	Environmental Quality Incentive Program
GWLF	Generalized Watershed Loading Function
HSG	Hydrologic Soil Group
ISW	Industrial Stormwater
JMU	James Madison University
LA	Load Allocation
LTA	Long-Term Average
MDL	Maximum Daily Load
MOS	Margin of Safety
MS4	Municipal Separate Storm Sewer Systems
NCDC	National Climate Data Center
NPDES	National Pollutant Discharge Elimination System
NRCS	Natural Resource Conservation Service
POC	Pollutant(s) of Concern
SCS-CN	Soil Conservation Service Curve Number
SSURGO	Soil Survey Geographic database
SWCB	State Water Control Board
SWCD	Soil and Water Conservation District
TAC	Technical Advisory Committee
TMDL	Total Maximum Daily Load
TP	Total Phosphorus
TSS	Total Suspended Sediment
USEPA	United States Environmental Protection Agency
USLE	Universal Soil Loss Equation
VADEQ	Virginia Department of Environmental Quality
VDOT	Virginia Department of Transportation
VGIN	Virginia Geographic Information Network
VPDES	Virginia Pollutant Discharge Elimination System
VSCI	Virginia Stream Condition Index
VSMP	Virginia Stormwater Management Program
WIP	Watershed Implementation Plan
WLA	Wasteload Allocation
WQMIRA	Water Quality Monitoring, Information and Restoration Act

1.0 EXECUTIVE SUMMARY

1.1. Background

This TMDL study spans six watersheds near Richmond and Petersburg, Virginia. These watersheds include Bailey Creek in Hopewell City and Prince George County, Nuttree Branch in Chesterfield County, Oldtown Creek in Chesterfield County and the City of Colonial Heights, Proctors Creek in Chesterfield County, Rohoic Creek in Dinwiddie County and City of Petersburg, and Swift Creek in Chesterfield and Powhatan Counties. All streams drain either directly or indirectly to the James River or Appomattox River (which itself is a tributary of the James).

> Definition:
>
> Watershed – All of the land area that drains to a particular point or body of water.

Bailey Creek, Nuttree Branch, Oldtown Creek, Proctors Creek, Rohoic Creek, and Swift Creek (herein collectively referred to as the "James River Tributaries") are listed as impaired on Virginia's 2020 Section 305(b)/303(d) Water Quality Assessment Integrated Report (IR) due to water quality violations of the general aquatic life (benthic) standard. The impaired segments addressed in this document are listed in **Table 1-1**. The watersheds of the impaired streams are shown in **Figure 1-1**.

Table 1-1. 2020 IR impaired segments addressed in this TMDL study.

TMDL Watershed	305(b) Segment ID	Cause Group Code 303(d) Impairment ID	Listing Station	Year Initially Listed
Bailey Creek	VAP-G03R_BLY02A08 (1.35 mi)	G03R-02-BEN	2-BLY005.73	2014
	VAP-G03R_BLY01A98 (5.12 mi)			2014
Nuttree Branch	VAP-J17R_NUT01A06 (5.58 mi)	J17R-06-BEN	2-NUT000.62	2012
Oldtown Creek	VAP-J15R_OTC01A00 (4.22 mi)	J15R-02-BEN	2-OTC001.54	2010
	VAP-J15R_OTC01B08 (6.22 mi)	J15R-08-BEN	2-OTC005.38	2018
Proctors Creek	VAP-G01R_PCT01A06 (8.26 mi)	G01R-15-BEN	2-PCT002.46	2010
Rohoic Creek	VAP-J15R_RHC01A06 (13.45 mi)	J15R-05-BEN	2-RHC000.58	2012
Swift Creek	VAP-J17R_SFT01B98 (7.25 mi)	J17R-01-BEN	2-SFT019.02	2010
	VAP-J17R_SFT02A00 (2.88 mi)	J17R-09-BEN	2-SFT025.32	2010

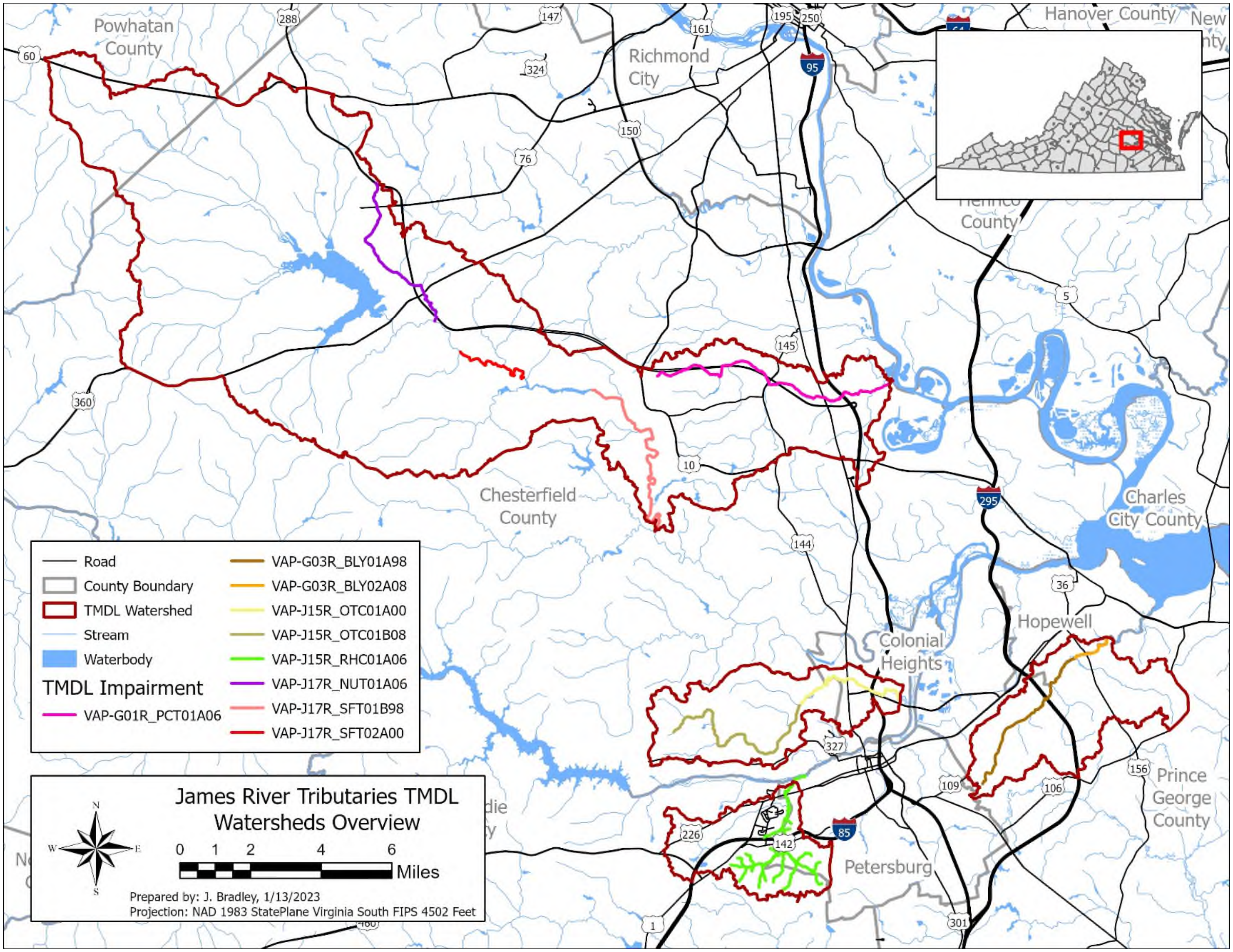

Figure 1-1. Location of the 2020 IR James River tributaries water impairments.

1.2. The Problem

1.2.1. Impaired Aquatic Life

The Commonwealth of Virginia sets standards for all the waters in the state. One of those standards is the expectation that every stream will support a healthy and diverse community of macroinvertebrates and fish (the aquatic life designated use). The Virginia Department of Environmental Quality (VADEQ) determines whether this standard is met by monitoring the benthic macroinvertebrate community (bugs that live on the bottom of the stream) in our waterways. The health and diversity of these bugs are assessed using the Virginia Stream Condition Index (VSCI). The VSCI is a multi-metric index used to derive stream health scores ranging from 0 to 100. Scores below 60 are categorized as impaired. **Figure 1-2** shows the various monitoring stations throughout the watershed, color-coded by the average score at each site. Red and yellow symbols indicate that the streams do not support a healthy and diverse community of macroinvertebrates and fish. This shows that the various impaired streams in this study fail the aquatic life use standard, and pollutants within the watershed need to be identified and reduced to help clean up the waterway.

A benthic stressor analysis study was conducted in 2021 to determine the reason for the benthic impairments in Bailey Creek, Nuttree Branch, Oldtown Creek, Proctors Creek, Rohoic Creek, and Swift Creek (**Appendix D**) (herein collectively referred to as the "James River Tributaries"). The study found that excess sediment was a cause of impairment across all watersheds, and excess phosphorus was determined to be an additional cause of impairment in Oldtown Creek, Rohoic Creek, and Swift Creek.

1.2.2. Too Much Sediment

Excess sediment was identified as a primary stressor in all study watersheds. When it rains, sediment is washed from the land surface into nearby creeks and rivers. The amount of soil that is washed off depends on how much it rains and the characteristics of the surrounding watershed. Rain falling on a construction site without sediment barriers or highly tilled cropland without a cover crop may carry a large amount of sediment to a stream. Other land types, like forests and well-maintained pasture, contribute much less sediment to waterways during rainfall events. When excess soil gets into nearby streams, it can fill in and destroy valuable habitat for aquatic macroinvertebrates that live underneath and between rocks on the bottom of the stream. Without this valuable habitat, the diversity of aquatic life in a stream may be severely limited.

1.2.3. Too Much Phosphorus

In addition to having too much sediment, Oldtown Creek, Rohoic Creek, and Swift Creek have too much phosphorus. Phosphorus is a nutrient that helps plants grow. Phosphorus can be found attached to the sediment that is washed into streams and can also be found in fertilizer and manure. Just as dirt can wash off of the land surface into nearby creeks, phosphorus contained in fertilizer and manure can wash off into streams. Too much phosphorus can cause excess algae to grow in a stream. When that algae dies and begins to decompose it can cause the oxygen supply in the water to dramatically decrease and limit the diversity of bugs and fish which need oxygen to survive.

1.3. The Study

To study the problem of excess sediment and phosphorus (where applicable) in the James River Tributaries TMDL, a combination of monitoring and computer modeling was utilized. Monitoring was used to tell how much sediment and phosphorus is in the streams at any given time and how aquatic life conditions have changed over time. The computer model was used to estimate where the sediment and phosphorus are coming from and make predictions about how stream conditions would change if those sources were reduced.

Frequently Asked Question:

Why use a computer model? Sampling and testing tell you a lot about the present and the past, but nothing about the future. A computer model is a tool that can help you make predictions about the future. This is necessary to figure out how much effort is needed to clean up a stream.

For this purpose, a computer numerical model called the Generalized Watershed Loading Function model (or GWLF) was used. This model considers slope, soils, land cover, erodibility, and runoff to estimate the amount of soil and associated phosphorus eroded in the watershed and deposited in the stream. The model was calibrated against real-world flow measurements taken from a nearby stream to ensure that it was producing accurate results. The tested model was then used to estimate the sediment and phosphorus reductions that would be needed to completely restore a healthy aquatic benthic community to the impaired streams in the watershed.

Definition:

TMDL – Total Maximum Daily Load. This is the amount of a pollutant that a stream can receive and still meet water quality standards. The term TMDL is also used more generally to describe the state's formal process for cleaning up polluted streams.

This report summarizes the study and sets goals for a clean-up plan. The study is called a Total Maximum Daily Load (TMDL) study because it determines the maximum amount of a pollutant that can enter a waterbody without harming the stream or the organisms living in it.

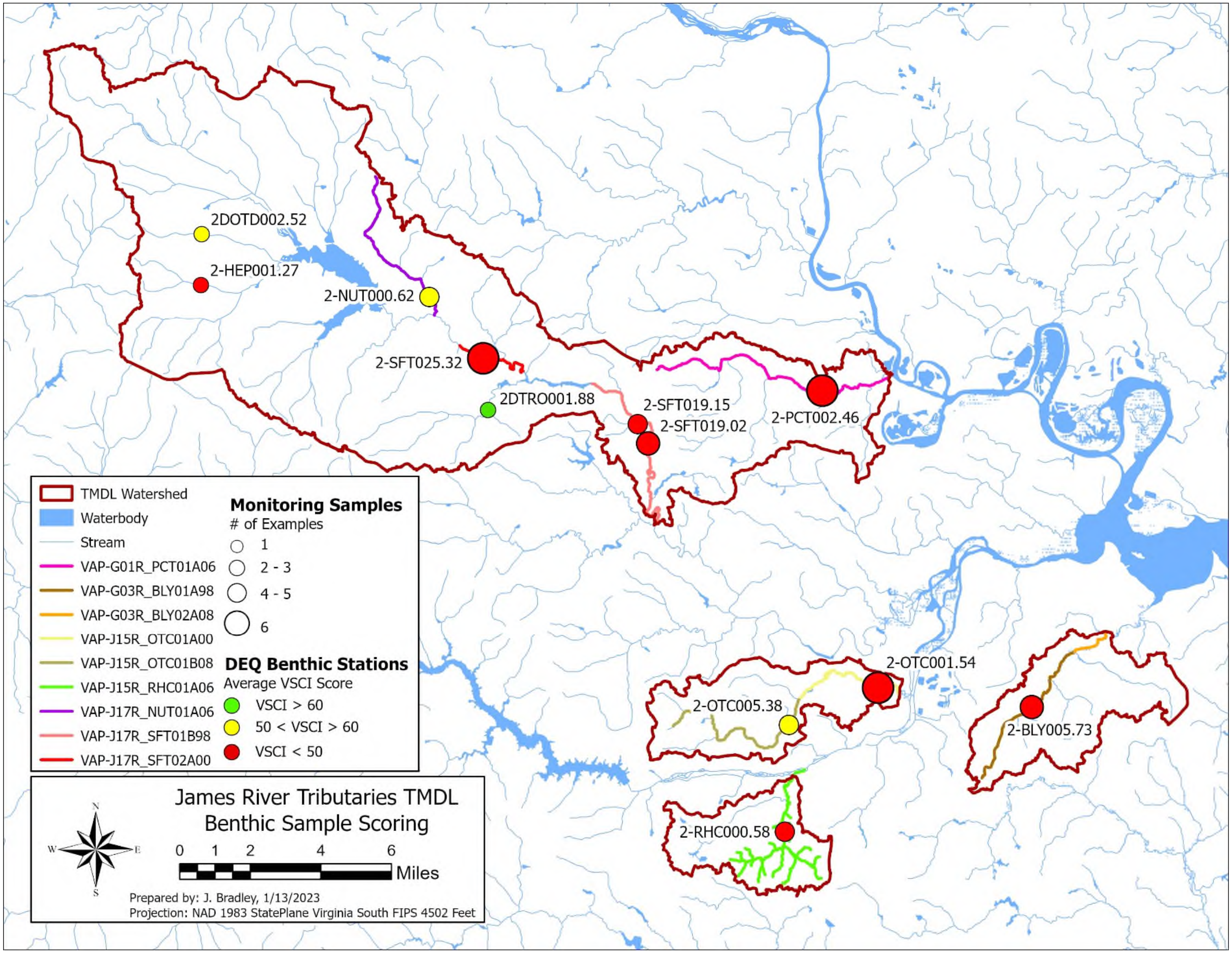

Figure 1-2. Stream health score summaries in the James River Tributaries watersheds.

1.4. Current Conditions

The Virginia Geographic Information Network (VGIN) 2016 Virginia Land Cover Dataset (VLCD) was used to determine current land use within the watersheds, with minor modifications (discussed in **Section 3.3**). The primary land cover in each watershed in this study is forest, followed by turfgrass and urban/suburban development. Agriculture (cropland and pasture/hay) is only a small percent of the land cover in each watershed. The land cover distribution for each impaired watershed is shown in **Figure 1-3** through **Figure 1-8.**

This land cover dataset combined with an accounting of the permitted discharges, represent the major pollutant sources in the watershed. The GWLF model was used to determine the relative contribution of sources of sediment and phosphorus in the impaired watersheds. **Figure 1-3** through **Figure 1-8** show the distribution of sediment and phosphorus (where applicable) contributions from various sources in the watersheds. Permitted sources include eight (8) Municipal Separate Storm Sewer System (MS4) entities: City of Colonial Heights, City of Hopewell, City of Petersburg, Central State Hospital, Chesterfield County, Fort Lee, John Tyler Community College, and Virginia Department of Transportation (VDOT). Additionally, the watersheds include Virginia Pollutant Discharge Elimination System (VPDES) individual permits, industrial stormwater permits, concrete general permits, domestic sewage permits, construction general permits, vehicle wash permits, and non-metallic mineral mining permits (NMMM). The sediment and phosphorus loads from permitted sources were calculated based on the permit language, reported discharge data, and land cover type and area (permits are detailed in **Section 4.3.2**). Due to the largely urban/suburban nature of the study watersheds, relatively little sediment or phosphorus is sourced from agricultural land and instead pollutant loads are driven by developed land uses, streambank erosion, and permitted discharges.

> Definition:
>
> <u>Point Source</u> – pollution that comes out of a pipe (like at a sewage treatment plant).
> <u>Non-point Source</u> – pollution that does not come out of a pipe but comes generally from the landscape (usually as runoff).

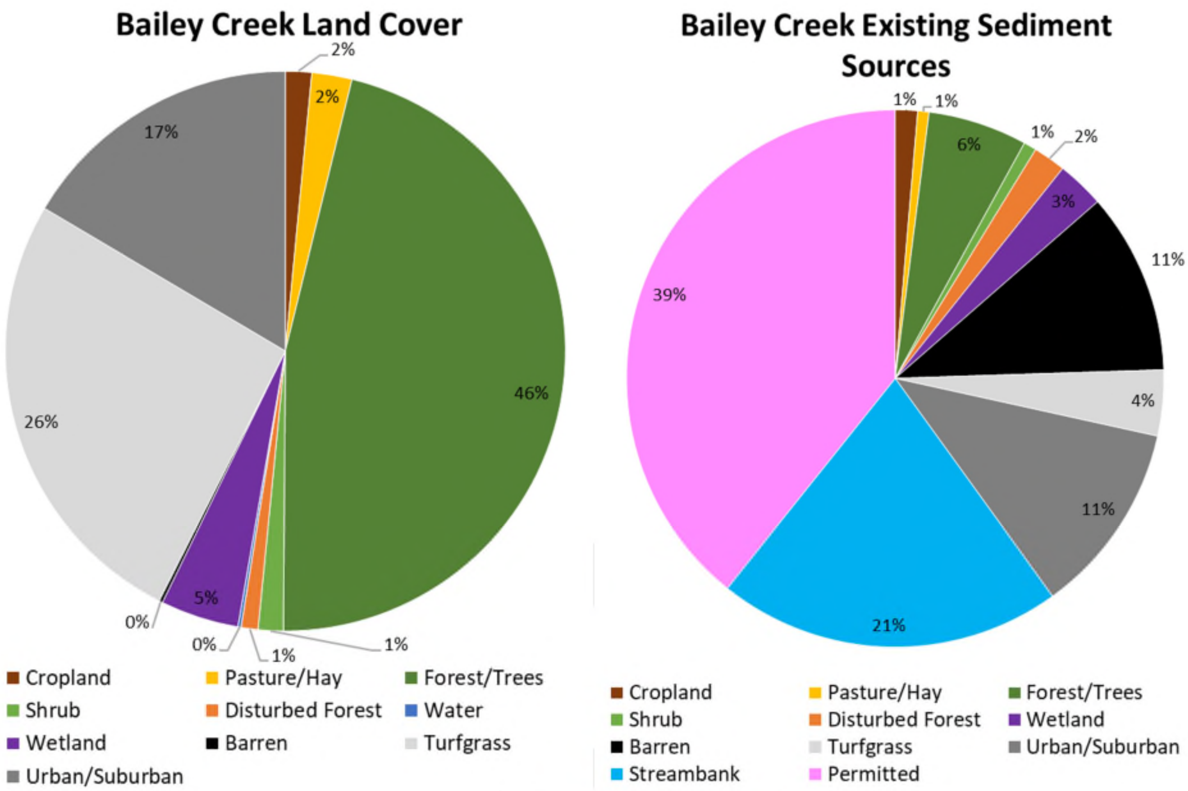

Figure 1-3. Land cover and existing source load distributions in the Bailey Creek watershed.

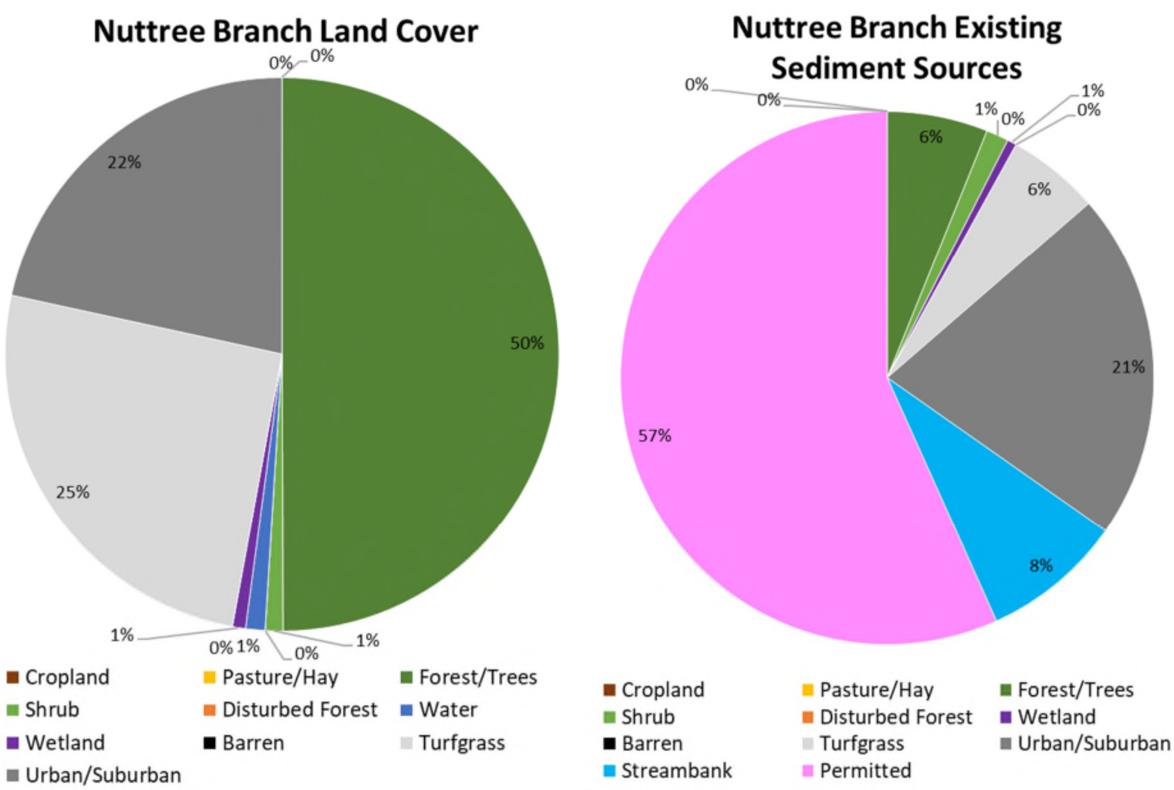

Figure 1-4. Land cover and existing source load distributions in the Nuttree Branch watershed.

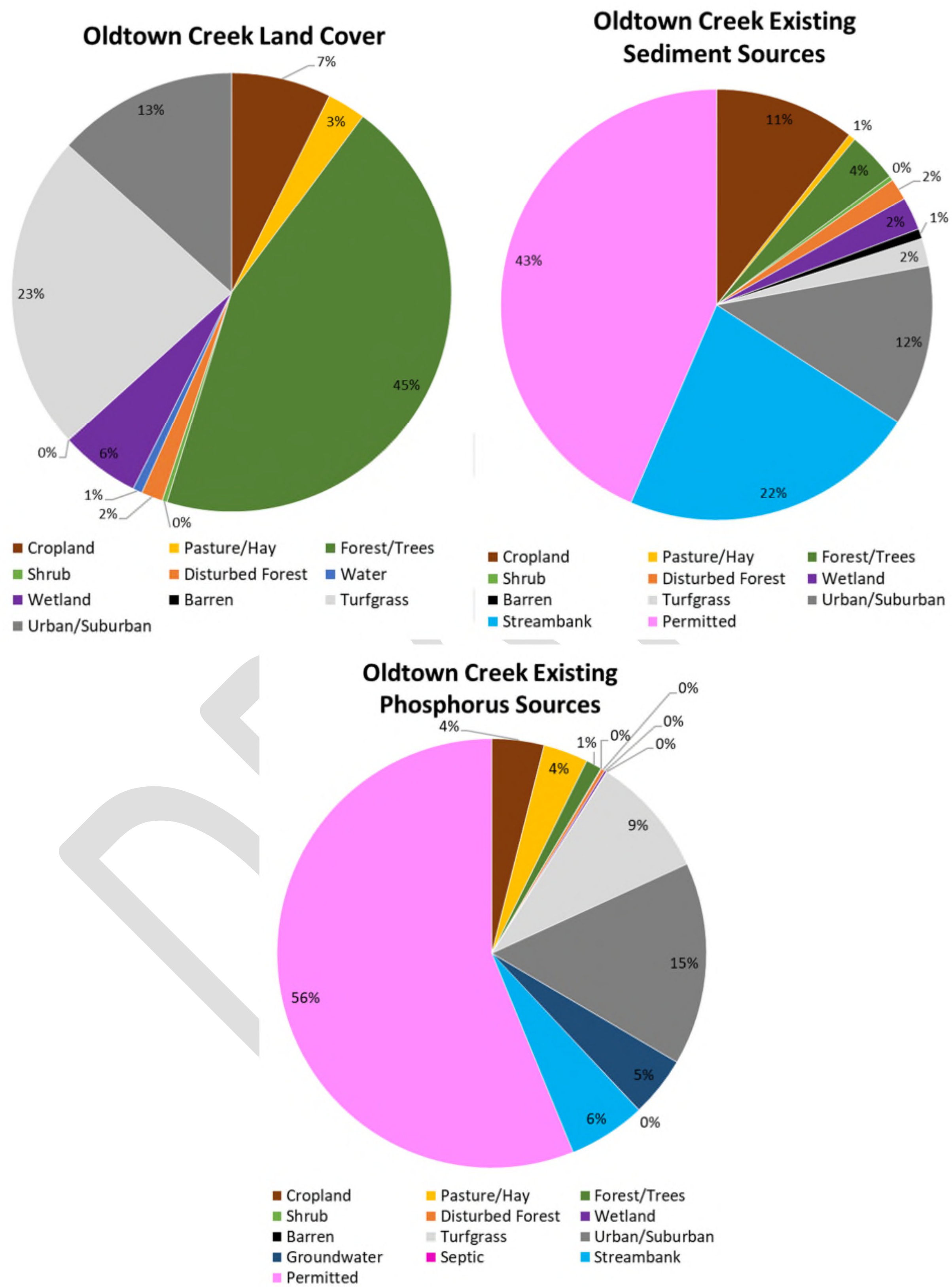

Figure 1-5. Land cover and existing source load distributions in the Oldtown Creek watershed.

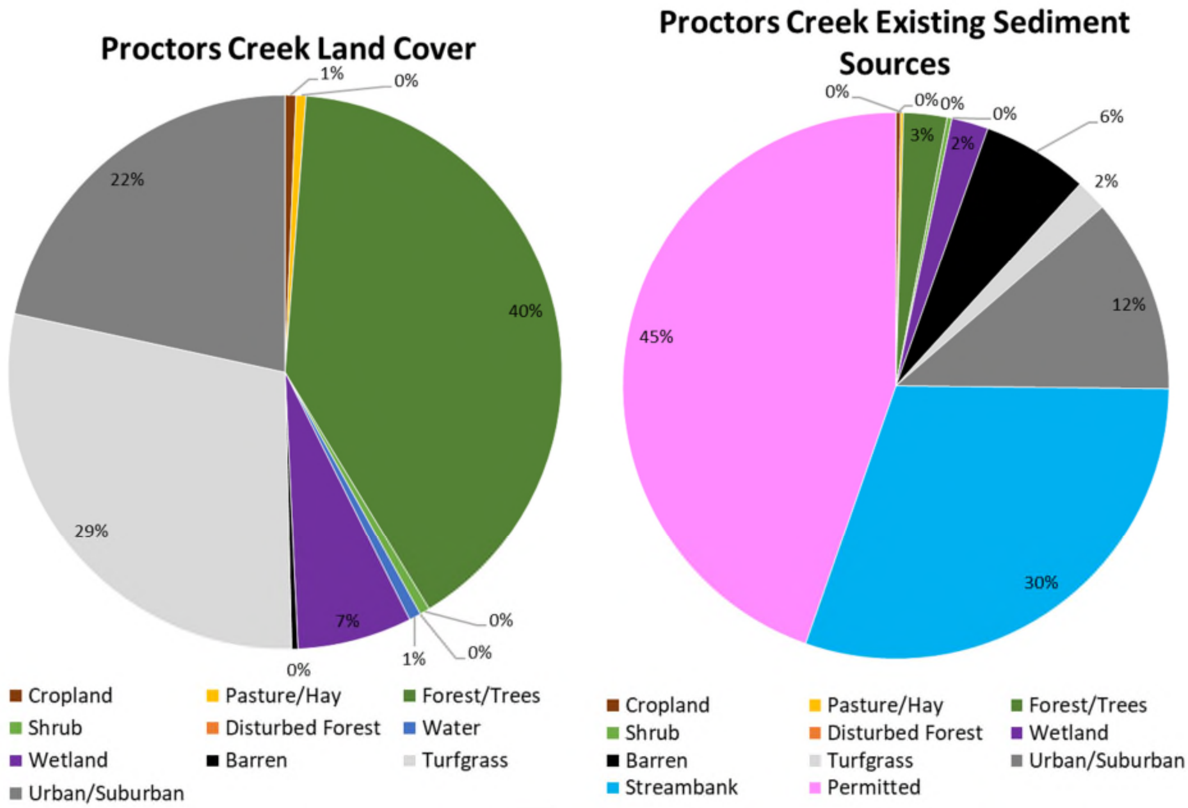

Figure 1-6. Land cover and existing source load distributions in the Proctors Creek watershed.

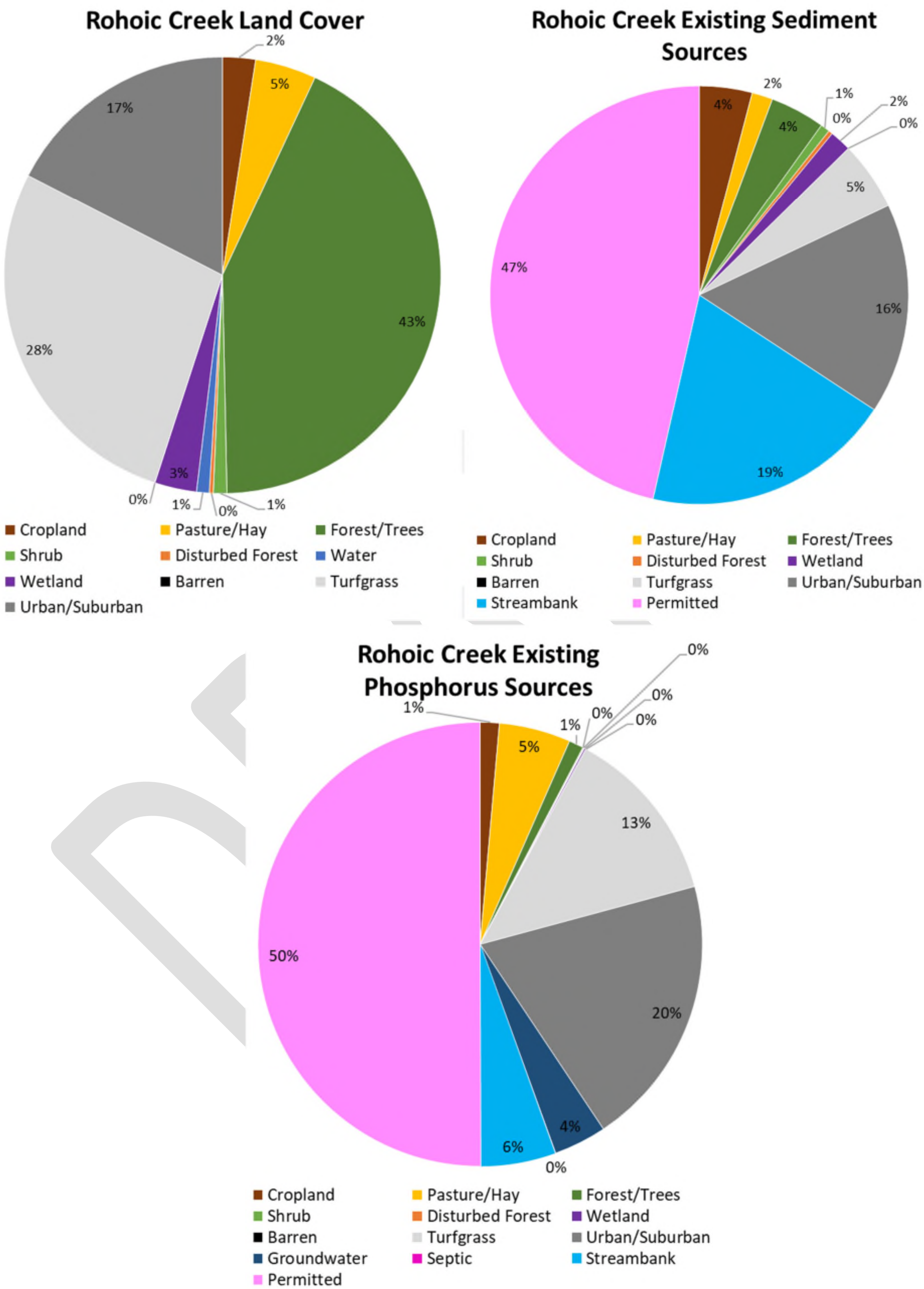

Figure 1-7. Land cover and existing source load distributions in the Rohoic Creek watershed.

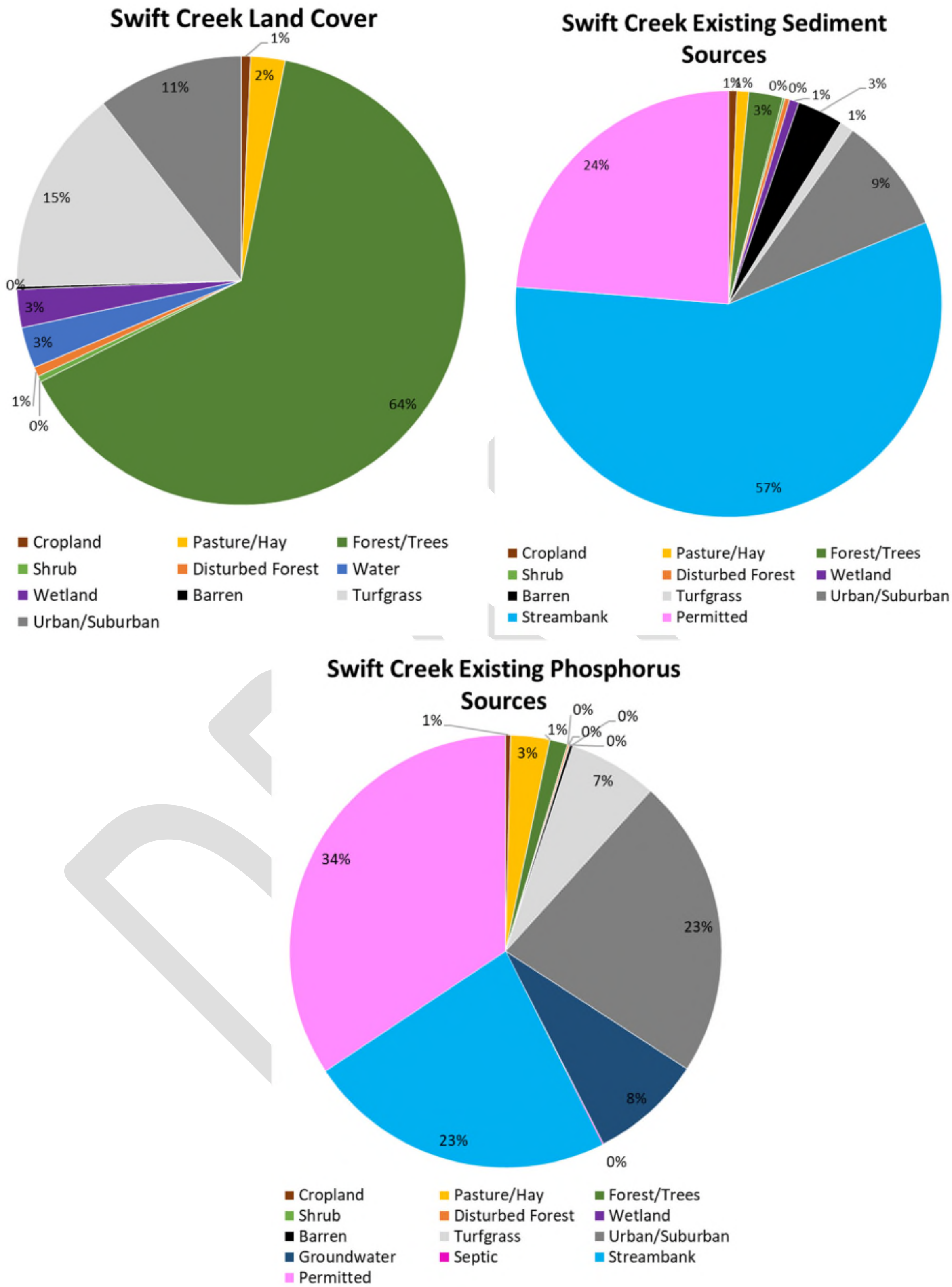

Figure 1-8. Land cover and existing source load distributions in the Swift Creek watershed.

1.5. Future Goals (the TMDL)

After determining existing sediment and phosphorus sources, a computer model was utilized to determine necessary load reductions needed to return the stream to a healthy condition. The goal for the impaired stream segments is to establish sediment and phosphorus levels that allow for diverse and abundant aquatic life without causing an undue burden on existing entities. The reductions in sediment and phosphorus needed to meet these goals are shown in **Table 1-2** and **Table 1-3.**

Table 1-2. Reductions in sediment needed to restore a healthy benthic community.

Watershed	Crop, Pasture, Hay	Forest, Trees, Shrubs, Wetland	Developed Pervious and Impervious Areas, Turfgrass*	Streambank Erosion	Permitted Sources**
Bailey Creek	54.5%	0.0%	54.5%	54.5%	0.0%
Nuttree Branch	N/A	0.0%	59.9%	59.9%	0.0%
Oldtown Creek	72.3%	0.0%	72.3%	72.3%	0.0%
Proctors Creek	88.4%	0.0%	88.4%	88.4%	0.0%
Rohoic Creek	79.8%	0.0%	79.8%	79.8%	50.0%
Swift Creek	57.0%	0.0%	57.0%	57.0%	0.0%

*Including MS4 permitted areas.

**Only industrial stormwater (ISW) permit loads are reduced in Rohoic Creek.

Table 1-3. Reductions in phosphorus needed to restore a healthy benthic community.

Watershed	Crop, Pasture, Hay	Forest, Trees, Shrubs, Wetland	Developed Pervious and Impervious Areas, Turfgrass*	Streambank Erosion	Permitted Sources**
Oldtown Creek	76.7%	0.0%	76.7%	76.7%	0.0%
Rohoic Creek	98.8%	0.0%	98.8%	98.8%	50%
Swift Creek	73.2%	0.0%	73.2%	73.2%	0.0%

*Including MS4 permitted areas.

**Only industrial stormwater (ISW) permit loads are reduced in Rohoic Creek.

To obtain healthy sediment levels in the impaired streams, significant reductions are needed from sediment and phosphorus sources. The total amount of sediment and phosphorus per year that would be entering each of these streams after the recommended reductions are made represent the total maximum daily load of the pollutant for each stream (**Table 1-4** to **Table 1-9** for sediment,

Table 1-10 to **Table 1-12** for phosphorus, model results rounded to 4 significant figures, calculations to 3). These annual loads are converted to daily maximum loads as well, as described in **Section 6.3** (**Table 1-13** to **Table 1-21**). If sediment and phosphorus loads are reduced to these amounts, healthy aquatic life should be restored in these streams.

Table 1-4. Annual average sediment TMDL components for Bailey Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TSS)	Allocated Nonpoint Sources (LA) (lb/yr TSS)	Margin of Safety (MOS) (lb/yr TSS)	Total Maximum Daily Load (TMDL) (lb/yr TSS)	Existing Load (lb/yr TSS)	Overall Reduction (%)
Bailey Creek (VAP-G03R_BLY02A08, VAP-G03R_BLY01A98)	**424,000**	**656,400**	**119,600**	**1,200,000**	2,130,000	43.7%
VA0059161	*5,245*					
Concrete Facility Permits	*1,945*					
ISW Permits	*43,060*					
MS4 Permits	*316,500*					
Construction Permits	*33,500*					
Future Growth (2% of TMDL)	*23,930*					

Table 1-5. Annual average sediment TMDL components for Nuttree Branch.

Impairment	Allocated Point Sources (WLA) (lb/yr TSS)	Allocated Nonpoint Sources (LA) (lb/yr TSS)	Margin of Safety (MOS) (lb/yr TSS)	Total Maximum Daily Load (TMDL) (lb/yr TSS)	Existing Load (lb/yr TSS)	Overall Reduction (%)
Nuttree Branch (VAP-J17R_NUT01A06)	**303,000**	**177,000**	**53,300**	**533,000**	861,000	38.1%
NMMM Permits	*45,700*					
Concrete Facility Permits	*326*					
ISW Permits	*8,888*					
MS4 Permits	*107,300*					
Construction Permits	*129,600*					
Future Growth (2% of TMDL)	*10,700*					

Table 1-6. Annual average sediment TMDL components for Oldtown Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TSS)	Allocated Nonpoint Sources (LA) (lb/yr TSS)	Margin of Safety (MOS) (lb/yr TSS)	Total Maximum Daily Load (TMDL) (lb/yr TSS)	Existing Load (lb/yr TSS)	Overall Reduction (%)
Oldtown Creek (VAP-J15R_OTC01A00 VAP-J15R_OTC01B08)	**253,000**	**308,500**	**62,520**	**624,000**	1,590,000	60.8%

MS4 Permits	*159,700*					
Construction Permits	*80,810*					
Future Growth (2% of TMDL)	*12,500*					

Table 1-7. Annual average sediment TMDL components for Proctors Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TSS)	Allocated Nonpoint Sources (LA) (lb/yr TSS)	Margin of Safety (MOS) (lb/yr TSS)	Total Maximum Daily Load (TMDL) (lb/yr TSS)	Existing Load (lb/yr TSS)	Overall Reduction (%)
Proctors Creek (VAP-G01R_PCT01A06)	**573,000**	**345,000**	**102,100**	**1,020,000**	3,290,000	69.0%
Concrete Facility Permits	*1,188*					
ISW Permits	*64,760*					
Vehicle Wash Permits	*55*					
MS4 Permits	*112,900*					
Construction Permits	*373,600*					
Future Growth (2% of TMDL)	*20,420*					

Table 1-8. Annual average sediment TMDL components for Rohoic Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TSS)	Allocated Nonpoint Sources (LA) (lb/yr TSS)	Margin of Safety (MOS) (lb/yr TSS)	Total Maximum Daily Load (TMDL) (lb/yr TSS)	Existing Load (lb/yr TSS)	Overall Reduction (%)
Rohoic Creek (VAP-J15R_RHC01A06)	**377,000**	**206,000**	**64,870**	**648,000**	1,360,000	52.4%
NMMM Permits	*127,900*					
Concrete Facility Permits	*4,586*					
ISW Permits	*57,800*					
MS4 Permits	*43,510*					
Construction Permits	*130,500*					
Future Growth (2% of TMDL)	*12,970*					

Table 1-9. Annual average sediment TMDL components for Swift Creek (Nuttree Branch represented within the LA).

Impairment	Allocated Permitted Point Sources (WLA) (lb/yr TSS)	Allocated Nonpoint Sources (LA) (lb/yr TSS)	Margin of Safety (MOS) (lb/yr TSS)	Total Maximum Daily Load (TMDL) (lb/yr TSS)	Existing Load (lb/yr TSS)	Overall Reduction (%)
Swift Creek (VAP-J17R_SFT01B98, VAP-J17R_SFT02A00)	**2,870,000**	**7,030,000**	**1,099,000**	**11,000,000**	20,100,000	45.3%
VA0006254	*91,380*					
VA0023426	*8,910*					
NMMM Permits	*137,100*					
ISW Permits	*101,700*					
Domestic Sewage Permits	*366*					
MS4 Permits	*993,200*					
Construction Permits	*1,314,000*					
Future Growth (2% of TMDL)	*219,800*					

Table 1-10. Annual average phosphorus TMDL components for Oldtown Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TP)	Allocated Nonpoint Sources (LA) (lb/yr TP)	Margin of Safety (MOS) (lb/yr TP)	Total Maximum Daily Load (TMDL) (lb/yr TP)	Existing Load (lb/yr TP)	Overall Reduction (%)
Oldtown Creek (VAP-J15R_OTC01A00, VAP-J15R_OTC01B08)	**404**	**407**	**91**	**902**	2,720	66.8%
MS4 Permits	*327.7*					
Construction Permits	*58.2*					
Future Growth (2% of TMDL)	*18.1*					

Table 1-11. Annual average phosphorus TMDL components for Rohoic Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TP)	Allocated Nonpoint Sources (LA) (lb/yr TP)	Margin of Safety (MOS) (lb/yr TP)	Total Maximum Daily Load (TMDL) (lb/yr TP)	Existing Load (lb/yr TP)	Overall Reduction (%)
Rohoic Creek (VAP-J15R_RHC01A06)	**426**	**163**	**65**	**654**	2,330	71.0%
NMMM Permits	*85.3*					
Concrete Facility Permits	*31.0*					
ISW Permits	*197.0*					
MS4 Permits	*6.3*					
Construction Permits	*94.0*					
Future Growth (2% of TMDL)	*13.1*					

Table 1-12. Annual average phosphorus TMDL components for Swift Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TP)	Allocated Nonpoint Sources (LA) (lb/yr TP)	Margin of Safety (MOS) (lb/yr TP)	Total Maximum Daily Load (TMDL) (lb/yr TP)	Existing Load (lb/yr TP)	Overall Reduction (%)
Swift Creek (VAP-J17R_SFT01B98, VAP-J17R_SFT02A00)	**3,150**	**4,700**	**873**	**8,720**	20,200	56.8%
VA0006254	*9.6*					
VA0023426	*46.0*					
NMMM Permits	*121.8*					
ISW Permits	*377.1*					
Domestic Sewage Permits	*17.2*					
MS4 Permits	*1,354*					
Construction Permits	*1,040*					
Future Growth (2% of TMDL)	*174.6*					

Table 1-13. Maximum 'daily' sediment loads and components for Bailey Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TSS)	Allocated Nonpoint Sources (LA) (lb/day TSS)	Margin of Safety (MOS) (lb/day TSS)	Maximum Daily Load (MDL) (lb/day TSS)
Bailey Creek (VAP-G03R_BLY02A08, VAP-G03R_BLY01A98)	**1,161**	**3,038**	**467**	**4,665**
VA0059161	*14.4*			
Concrete Facility Permits	*5.3*			
ISW Permits	*117.9*			
MS4 Permits	*866.6*			
Construction Permits	*91.7*			
Future Growth (2% of TMDL)	*65.5*			

Table 1-14. Maximum 'daily' sediment loads and components for Nuttree Branch.

Impairment	Allocated Point Sources (WLA) (lb/day TSS)	Allocated Nonpoint Sources (LA) (lb/day TSS)	Margin of Safety (MOS) (lb/day TSS)	Maximum Daily Load (MDL) (lb/day TSS)
Nuttree Branch (VAP-J17R_NUT01A06)	**830**	**1,101**	**215**	**2,145**
NMMM Permits	*125.1*			
Concrete Facility Permits	*0.9*			
ISW Permits	*24.3*			
MS4 Permits	*293.8*			
Construction Permits	*355*			
Future Growth (2% of TMDL)	*29*			

Table 1-15. Maximum 'daily' sediment loads and components for Oldtown Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TSS)	Allocated Nonpoint Sources (LA) (lb/day TSS)	Margin of Safety (MOS) (lb/day TSS)	Maximum Daily Load (MDL) (lb/day TSS)
Oldtown Creek (VAP-J15R_OTC01A00 VAP-J15R_OTC01B08)	**693**	**1,491**	**243**	**2,426**
MS4 Permits	*437.2*			
Construction Permits	*221.3*			
Future Growth (2% of TMDL)	*34.2*			

Table 1-16. Maximum 'daily' sediment loads and components for Proctors Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TSS)	Allocated Nonpoint Sources (LA) (lb/day TSS)	Margin of Safety (MOS) (lb/day TSS)	Maximum Daily Load (MDL) (lb/day TSS)
Proctors Creek (VAP-G01R_PCT01A06)	**1,569**	**2,025**	**399**	**3,994**
Concrete Facility Permits	*3.3*			
ISW Permits	*177.3*			
Vehicle Wash Permits	*0.2*			
MS4 Permits	*309.1*			
Construction Permits	*1,023*			
Future Growth (2% of TMDL)	*56*			

Table 1-17. Maximum 'daily' sediment loads and components for Rohoic Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TSS)	Allocated Nonpoint Sources (LA) (lb/day TSS)	Margin of Safety (MOS) (lb/day TSS)	Maximum Daily Load (MDL) (lb/day TSS)
Rohoic Creek (VAP-J15R_RHC01A06)	**1,032**	**1,235**	**252**	**2,519**
NMMM Permits	*350.2*			
Concrete Facility Permits	*12.6*			
ISW Permits	*158.3*			
MS4 Permits	*119.1*			
Construction Permits	*357*			
Future Growth (2% of TMDL)	*36*			

Table 1-18. Maximum 'daily' sediment loads and components for Swift Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TSS)	Allocated Nonpoint Sources (LA) (lb/day TSS)	Margin of Safety (MOS) (lb/day TSS)	Maximum Daily Load (MDL) (lb/day TSS)
Swift Creek (VAP-J17R_SFT01B98, VAP-J17R_SFT02A00)	**7,858**	**30,632**	**4,277**	**42,766**
VA0006254	*250.2*			
VA0023426	*24.4*			
NMMM Permits	*375.4*			
ISW Permits	*278.4*			
Domestic Sewage Permits	*1.0*			
MS4 Permits	*2,719.3*			
Construction Permits	*3,598*			
Future Growth (2% of TMDL)	*602*			

Table 1-19. Maximum ‘daily’ phosphorus loads and components for Oldtown Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TP)	Allocated Nonpoint Sources (LA) (lb/day TP)	Margin of Safety (MOS) (lb/day TP)	Maximum Daily Load (MDL) (lb/day TP)
Oldtown Creek (VAP-J15R_OTC01A00 VAP-J15R_OTC01B08)	**1.1**	**2.3**	**0.4**	**3.8**
MS4 Permits	*0.9*			
Construction Permits	*0.2*			
Future Growth (2% of TMDL)	*0.05*			

Table 1-20. Maximum ‘daily’ phosphorus loads and components for Rohoic Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TP)	Allocated Nonpoint Sources (LA) (lb/day TP)	Margin of Safety (MOS) (lb/day TP)	Maximum Daily Load (MDL) (lb/day TP)
Rohoic Creek (VAP-J15R_RHC01A06)	**1.2**	**1.4**	**0.3**	**2.8**
NMMM Permits	*0.2*			
Concrete Facility Permits	*0.1*			
ISW Permits	*0.5*			
MS4 Permits	*0.0*			
Construction Permits	*0.3*			
Future Growth (2% of TMDL)	*0.04*			

Table 1-21. Maximum ‘daily’ phosphorus loads and components for Swift Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TP)	Allocated Nonpoint Sources (LA) (lb/day TP)	Margin of Safety (MOS) (lb/day TP)	Maximum Daily Load (MDL) (lb/day TP)
Swift Creek (VAP-J17R_SFT01B98, VAP-J17R_SFT02A00)	**8.6**	**24.0**	**3.6**	**36.3**
VA0006254	*0.03*			
VA0023426	*0.1*			
NMMM Permits	*0.3*			
ISW Permits	*1.0*			
Domestic Sewage Permits	*0.05*			
MS4 Permits	*3.7*			
Construction Permits	*2.8*			
Future Growth (2% of TMDL)	*0.5*			

1.5.1. Allocation Scenarios

There are many ways to reduce pollutants to reach TMDL goals. Several versions of these reduction plans, or allocation scenarios, were developed. These were presented to the Technical Advisory Committee which determined that Scenario 1 was preferred for each watershed (see **Table 1-22** through **Table 1-30**) . Model results were rounded to four significant figures, and calculated totals of those results were rounded to three significant figures.

Table 1-22. Allocation scenarios for Bailey Creek sediment loads.

Bailey Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**
Cropland	26,620	54.5	12,110	40.8	15,760	77.1	6,096
Hay	6,796	54.5	3,092	40.8	4,024	77.1	1,556
Pasture	6,592	54.5	2,999	40.8	3,902	77.1	1,510
Forest	52,790	-	52,790	-	52,790	-	52,790
Trees	65,790	-	65,790	-	65,790	-	65,790
Shrub	15,240	-	15,240	-	15,240	-	15,240
Harvested	38,880	54.5	17,690	40.8	23,020	77.1	8,904
Wetland	56,730	-	56,730	-	56,730	-	56,730
Barren	216,700	54.5	98,610	60.0	86,690	45.5	118,100
Turfgrass	78,630	54.5	35,780	60.0	31,450	45.5	42,850
Developed Pervious	10,940	54.5	4,975	60.0	4,374	45.5	5,960
Developed Impervious	219,200	54.5	99,720	60.0	87,660	45.5	119,400
Streambank Erosion	410,600	54.5	186,800	40.8	243,100	77.1	94,020
VA0059161	5,245	-	5,245	-	5,245	-	5,245
Concrete Facility Permits	1,945	-	1,945	-	1,945	-	1,945
ISW Permits	43,060	-	43,060	-	43,060	-	43,060
MS4	695,700	54.5	316,500	60.0	278,300	45.5	379,100
Construction Permits	33,500	-	33,500	-	33,500	-	33,500
Future Growth (2%)	23,930	-	23,930	-	23,930	-	23,930
MOS (10%)	119,600	-	119,600	-	119,600	-	119,600
TOTAL	**2,130,000**	**43.7**	**1,200,000**	**43.7**	**1,200,000**	**43.7**	**1,200,000**

Table 1-23. Allocation scenarios for Nuttree Branch sediment loads.

Nuttree Branch Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**
Cropland	-	-	-	-	-	-	-
Hay	-	-	-	-	-	-	-
Pasture	-	-	-	-	-	-	-
Forest	16,410	-	16,410	-	16,410	-	16,410
Trees	32,270	-	32,270	-	32,270	-	32,270
Shrub	10,830	-	10,830	-	10,830	-	10,830
Harvested	-	-	-	-	-	-	-
Wetland	4,520	-	4,520	-	4,520	-	4,520
Barren	-	-	-	68.4	-	62.7	-
Turfgrass	44,640	59.9	17,900	68.4	14,110	62.7	16,650
Developed Pervious	3,547	59.9	1,422	68.4	1,121	62.7	1,323
Developed Impervious	164,700	59.9	66,040	68.4	52,040	62.7	61,430
Streambank Erosion	68,130	59.9	27,320	-	68,130	40.0	40,880
NMMM Permits	45,690	-	45,690	-	45,690	-	45,690
Concrete Facility Permits	326	-	326	-	326	-	326
ISW Permits	8,888	-	8,888	-	8,888	-	8,888
MS4	267,500	59.9	107,300	68.4	84,550	62.7	99,800
Construction Permits	129,600	-	129,600	-	129,600	-	129,600
Future Growth (2%)	10,660	-	10,660	-	10,660	-	10,660
MOS (10%)	53,280	-	53,280	-	53,280	-	53,280
TOTAL	**861,000**	**38.2**	**532,000**	**38.2**	**532,000**	**38.1**	**533,000**

Table 1-24. Allocation scenarios for Oldtown Creek sediment loads.

Oldtown Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**
Cropland	159,200	72.3	44,090	40.0	95,510	81.5	29,450
Hay	6,105	72.3	1,691	40.0	3,663	81.5	1,129
Pasture	1,690	72.3	468	40.0	1,014	81.5	313
Forest	37,250	-	37,250	-	37,250	-	37,250
Trees	19,720	-	19,720	-	19,720	-	19,720
Shrub	5,024	-	5,024	-	5,024	-	5,024
Harvested	24,670	72.3	6,834	40.0	14,800	81.5	4,564
Wetland	37,550	-	37,550	-	37,550	-	37,550
Barren	11,290	72.3	3,127	77.7	2,517	81.5	2,088
Turfgrass	31,170	72.3	8,635	77.7	6,952	81.5	5,767
Developed Pervious	3,218	72.3	891	77.7	718	81.5	595
Developed Impervious	179,100	72.3	49,620	77.7	39,940	81.5	33,140
Streambank Erosion	337,800	72.3	93,580	77.7	75,340	45.0	185,800
MS4	576,600	72.3	159,700	77.7	128,600	81.5	106,700
Construction Permits	80,810	-	80,810	-	80,810	-	80,810
Future Growth (2%)	12,500	-	12,500	-	12,500	-	12,500
MOS (10%)	62,520	-	62,520	-	62,520	-	62,520
TOTAL	**1,590,000**	**60.8**	**624,000**	**60.8**	**624,000**	**60.7**	**625,000**

Table 1-25. Allocation scenarios for Proctors Creek sediment loads.

Proctors Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**
Cropland	8,824	88.4	1,024	-	8,824	50.0	4,412
Hay	2,111	88.4	245	-	2,111	50.0	1,055
Pasture	3,043	88.4	353	-	3,043	50.0	1,521
Forest	36,460	-	36,460	-	36,460	-	36,460
Trees	45,160	-	45,160	-	45,160	-	45,160
Shrub	8,735	-	8,735	-	8,735	-	8,735
Harvested	-	88.4	-	-	-	50.0	-
Wetland	68,880	-	68,880	-	68,880	-	68,880
Barren	199,600	88.4	23,160	88.9	22,160	88.6	22,760
Turfgrass	58,680	88.4	6,807	88.9	6,514	88.6	6,690
Developed Pervious	4,151	88.4	482	88.9	461	88.6	473
Developed Impervious	361,100	88.4	41,880	88.9	40,080	88.6	41,160
Streambank Erosion	955,900	88.4	110,900	88.9	106,100	88.6	109,000
Concrete Facility Permits	1,188	-	1,188	-	1,188	-	1,188
Vehicle Wash Permits	55	-	55	-	55	-	55
ISW Permits	64,760	-	64,760	-	64,760	-	64,760
MS4	973,100	88.4	112,900	88.9	108,000	88.6	110,900
Construction Permits	373,600	-	373,600	-	373,600	-	373,600
Future Growth (2%)	20,420	-	20,420	-	20,420	-	20,420
MOS (10%)	102,100	-	102,100	-	102,100	-	102,100
TOTAL	**3,290,000**	**69.0**	**1,020,000**	**69.0**	**1,020,000**	**69.0**	**1,020,000**

Table 1-26. Allocation scenarios for Rohoic Creek sediment loads.

Rohoic Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**
Cropland	52,140	79.8	10,530	77.3	11,840	80.0	10,430
Hay	16,410	79.8	3,314	77.3	3,724	80.0	3,281
Pasture	4,153	79.8	839	77.3	943	80.0	831
Forest	22,270	-	22,270	-	22,270	-	22,270
Trees	31,910	-	31,910	-	31,910	-	31,910
Shrub	9,145	-	9,145	-	9,145	-	9,145
Harvested	4,129	79.8	834	77.3	937	80.0	826
Wetland	21,340	-	21,340	-	21,340	-	21,340
Barren	-	79.8	-	80.0	-	79.6	-
Turfgrass	68,250	79.8	13,790	80.0	13,650	79.6	13,920
Developed Pervious	9,356	79.8	1,890	80.0	1,871	79.6	1,909
Developed Impervious	198,800	79.8	40,160	80.0	39,760	79.6	40,560
Streambank Erosion	247,200	79.8	49,930	80.0	49,430	80.0	49,430
NMMM Permits	127,900	-	127,900	-	127,900	-	127,900
Concrete Facility Permits	4,586	-	4,586	-	4,586	-	4,586
ISW Permits	115,600	50.0	57,800	50.0	57,800	50.0	57,800
MS4	215,400	79.8	43,510	80.0	43,080	79.6	43,950
Construction Permits	130,500	-	130,500	-	130,500	-	130,500
Future Growth (2%)	12,970	-	12,970	-	12,970	-	12,970
MOS (10%)	64,870	-	64,870	-	64,870	-	64,870
TOTAL	**1,360,000**	**52.4**	**648,000**	**52.3**	**649,000**	**52.4**	**648,000**

Table 1-27. Allocation scenarios for Swift Creek sediment loads.

Swift Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3		Scenario 4	
Source	Existing TSS (lb/yr)	Reduction (%)	Allocation TSS (lb/yr)	Reduction (%)	Allocation TSS (lb/yr)	Reduction (%)	Allocation TSS (lb/yr)	Reduction (%)	Allocation TSS (lb/yr)
Cropland	119,500	57.0	51,390	39.6	72,180	83.2	20,080	-	119,500
Hay	26,210	57.0	11,270	39.6	15,830	83.2	4,404	-	26,210
Pasture	144,700	57.0	62,210	39.6	87,380	83.2	24,310	-	144,700
Forest	305,700	-	305,700	-	305,700	-	305,700	-	305,700
Trees	142,300	-	142,300	-	142,300	-	142,300	-	142,300
Shrub	19,860	-	19,860	-	19,860	-	19,860	-	19,860
Harvested	70,200	57.0	30,190	39.6	42,400	83.2	11,790	-	70,200
Wetland	134,300	-	134,300	-	134,300	-	134,300	-	134,300
Barren	668,000	57.0	287,200	39.6	403,500	83.2	112,200	58.4	277,900
Turfgrass	155,500	57.0	66,860	39.6	93,910	83.2	26,120	58.4	64,680
Developed Pervious	20,960	57.0	9,015	39.6	12,660	83.2	3,522	58.4	8,721
Developed Impervious	1,517,000	57.0	652,100	39.6	916,000	83.2	254,800	58.4	630,900
Streambank Erosion	10,970,000	57.0	4,717,000	65.0	3,839,000	45.0	6,033,000	58.4	4,563,000
VA0006254	91,380	-	91,380	-	91,380	-	91,380	-	91,380
VA0023426	8,910	-	8,910	-	8,910	-	8,910	-	8,910
NMMM Permits	137,072	-	137,072	-	137,072	-	137,072	-	137,072
Domestic Sewage Permits	366	-	366	-	366	-	366	-	366
ISW Permits	101,700	-	101,700	-	101,700	-	101,700	-	101,700
MS4	2,310,000	57.0	993,200	39.6	1,395,000	83.2	388,000	58.4	960,900
Construction Permits	1,314,000	-	1,314,000	-	1,314,000	-	1,314,000	-	1,314,000
Future Growth (2%)	219,800	-	219,800	-	219,800	-	219,800	-	219,800
Nuttree Branch TMDL Target	533,000	-	533,000	-	533,000	-	533,000	-	533,000
MOS (10%)	1,099,000	-	1,099,000	-	1,099,000	-	1,099,000	-	1,099,000
TOTAL	**20,100,000**	**45.3**	**11,000,000**	**45.3**	**11,000,000**	**45.3**	**11,000,000**	**45.3**	**11,000,000**

Table 1-28. Allocation scenarios for Oldtown Creek phosphorus loads.

Oldtown Creek Watershed		**Scenario 1 (preferred)**		**Scenario 2**		**Scenario 3**	
Source	**Existing TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**
Cropland	102.4	76.7	23.9	50.0	51.2	78.7	21.8
Hay	84.8	76.7	19.8	50.0	42.4	78.7	18.1
Pasture	3.1	76.7	0.7	50.0	1.5	78.7	0.6
Forest	18.0	-	18.0	-	18.0	-	18.0
Trees	13.4	-	13.4	-	13.4	-	13.4
Shrub	0.9	-	0.9	-	0.9	-	0.9
Harvested	7.1	76.7	1.7	50.0	3.6	78.7	1.5
Wetland	4.1	-	4.1	-	4.1	-	4.1
Barren	1.3	76.7	0.3	79.2	0.3	78.7	0.3
Turfgrass	238.6	76.7	55.6	79.2	49.6	78.7	50.8
Developed Pervious	4.7	76.7	1.1	79.2	1.0	78.7	1.0
Developed Impervious	394.1	76.7	91.8	79.2	82.0	78.7	83.9
Streambank Erosion	118.2	76.7	27.6	79.2	24.6	40.0	71.0
Septic	0.9	76.7	0.2	79.2	0.2	78.7	0.2
Groundwater	150.9	-	150.9	-	150.9	-	150.9
MS4	1,406.0	76.7	327.7	79.2	292.5	78.7	299.6
Construction Permits	58.2	-	58.2	-	58.2	-	58.2
Future Growth (2%)	18.1	-	18.1	-	18.1	-	18.1
MOS (10%)	90.5	-	90.5	-	90.5	-	90.5
TOTAL	**2,720.0**	**66.8**	**904.0**	**66.8**	**903.0**	**66.8**	**903.0**

Table 1-29. Allocation scenarios for Rohoic Creek phosphorus loads. Scenario 2 does not meet target reductions.

Rohoic Creek Watershed		**Scenario 1 (preferred)**		**Scenario 2**	
Source	**Existing TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**
Cropland	31.3	98.8	0.4	100.0	-
Hay	113.1	98.8	1.4	100.0	-
Pasture	4.1	98.8	0.0	100.0	-
Forest	9.7	-	9.7	-	9.7
Trees	14.3	-	14.3	-	14.3
Shrub	1.5	-	1.5	-	1.5
Harvested	1.2	98.8	0.0	100.0	-
Wetland	2.6	-	2.6	-	2.6
Barren	-	-	-	-	-
Turfgrass	290.9	98.8	3.5	100.0	-
Developed Pervious	9.7	98.8	0.1	100.0	-
Developed Impervious	437.4	98.8	5.2	100.0	-
Streambank Erosion	86.5	98.8	1.0	100.0	-
Septic	0.9	98.8	0.0	100.0	-
Groundwater	122.3	-	122.3	-	122.3
NMMM Permits	85.3	-	85.3	-	85.3
Concrete Facility Permits	31.0	-	31.0	-	31.0
ISW Permits	394.1	50.0	197.0	-	394.1
MS4	523.4	98.8	6.3	100.0	-
Construction Permits	94.0	-	94.0	-	94.0
Future Growth (2%)	13.1	-	13.1	-	13.1
MOS (10%)	65.4	-	65.4	-	65.4
TOTAL	**2,330.0**	**71.9**	**654.0**	**64.2**	**833.0**

Table 1-30. Allocation scenarios for Swift Creek phosphorus loads (inclusive of Nuttree Branch).

Swift Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**
Cropland	70.9	73.2	19.0	25.0	53.2	82.2	12.6
Hay	362.6	73.2	97.2	25.0	271.9	82.2	64.5
Pasture	190.9	73.2	51.2	25.0	143.2	82.2	34.0
Forest	143.3	-	143.3	-	143.3	-	143.3
Trees	115.1	-	115.1	-	115.1	-	115.1
Shrub	2.5	-	2.5	-	2.5	-	2.5
Harvested	22.6	73.2	6.1	25.0	16.9	82.2	4.0
Wetland	7.9	-	7.9	-	7.9	-	7.9
Barren	43.7	73.2	11.7	75.3	10.8	82.2	7.8
Turfgrass	1,267.0	73.2	339.5	75.3	312.9	82.2	225.5
Developed Pervious	35.3	73.2	9.5	75.3	8.7	82.2	6.3
Developed Impervious	4,237.0	73.2	1,135.0	75.3	1,046.0	82.2	754.1
Streambank Erosion	4,383.0	73.2	1,175.0	75.3	1,083.0	50.0	2,191.0
Septic	17.4	73.2	4.7	75.3	4.3	82.2	3.1
Groundwater	1,588.0	-	1,588.0	-	1,588.0	-	1,588.0
VA0006254	9.6	-	9.6	-	9.6	-	9.6
VA0023426	46.0	-	46.0	-	46.0	-	46.0
NMMM Permits	121.8	-	121.8	-	121.8	-	121.8
Domestic Sewage Permits	17.2	-	17.2	-	17.2	-	17.2
ISW Permits	377.1	-	377.1	-	377.1	-	377.1
MS4	5,071.0	73.2	1,359.0	75.3	1,253.0	82.2	902.7
Construction Permits	1,040.0	-	1,040.0	-	1,040.0	-	1,040.0
Future Growth (2%)	174.6	-	174.6	-	174.6	-	174.6
MOS (10%)	873.0	-	873.0	-	873.0	-	873.0
TOTAL	**20,200.0**	**56.8**	**8,730.0**	**56.8**	**8,720.0**	**56.8**	**8,720.0**

1.6. Public Participation

Throughout this study, VADEQ asked for help from local residents and knowledgeable stakeholders – those who have a particular interest in or may be affected by the outcome of the project. Public participation keeps stakeholders informed, and it allows for stakeholder input to ensure information in the study is accurate. While the project was progressing, VADEQ held two public meetings and three Technical Advisory Committee (TAC) meetings. The final public meeting was held on February 15, 2023 to present the draft TMDL document and begin the official public comment period.

1.7. Reasonable Assurance

Public participation in the development of the TMDL and any subsequent implementation plans, follow-up monitoring, permit action plans developed and implemented by MS4 permit holders, other permit compliance, and current implementation progress within the watersheds all combine to provide reasonable assurance that these TMDLs will be implemented and water quality will be restored in the impaired watersheds.

1.8. What Happens Next

VADEQ will receive public comment on this report and then submit it to the U.S. Environmental Protection Agency (USEPA) for approval. This report sets the clean-up goals (or TMDL) for the James River tributaries, but the next step is a clean-up plan (or Implementation Plan) that lays out how those goals will be reached. Clean-up plans set intermediate goals and describe actions that should be taken to improve water quality in the impaired streams. Examples of the potential actions that could be included in an implementation plan for the James River tributaries are listed below:

- Conduct stream bank restoration projects in areas where banks are actively eroding
- Leave a band of 35 – 100 ft along the stream natural so that it buffers or filters out sediment from farm or residential land (a riparian buffer)
- Expanded street sweeping programs in urban areas
- Reduce runoff by increasing green spaces and reducing hardened spaces (asphalt or concrete)

Frequently Asked Question:

How will the TMDL be implemented? For point sources, TMDL reductions will be implemented through discharge permits. For nonpoint sources, TMDL reductions will be implemented through best management practices (BMPs). Landowners will be asked to voluntarily participate in state and federal programs that help defer the cost of BMP installation.

These and other actions that could be included in a clean-up plan are identified in the planning process along with associated costs and the extent of each action needed. The clean-up plan also identifies potential sources of money to help with the clean-up efforts. Most of the money utilized to implement actions in the watersheds to date has been in the form of cost-share programs, which share the cost of improvements with the landowner. Additional funds for urban stormwater practices have been made available through various grants, including an annual funding opportunity through the National Fish and Wildlife Foundation's Chesapeake Bay Stewardship Fund program. Please be aware that the state or federal government will not fix the problems with the impaired streams. It is primarily the responsibility of individual landowners and local governments to take the actions necessary to improve these streams. The role of state agencies is to help with developing the plan and find money to support implementation, but actually making the improvements is up to those that live in the watershed. By increasing education and awareness of the problem, and by working together to each do our part, we can make the changes necessary to improve the streams.

VADEQ will continue to sample aquatic life in these streams and monitor the progress of the clean-up. This sampling will let us know when the clean-up has reached certain milestones listed in the plan. To begin moving towards these clean-up goals, VADEQ recommends that concerned citizens come together and begin working with local governments, civic groups, soil and water conservation districts, and local health districts to increase education and awareness of the problem and promote those activities and programs that improve stream health.

2.0 INTRODUCTION

2.1. Watershed Location and Description

The Bailey Creek watershed is approximately 9,100 acres and lies in the City of Hopewell and Prince George County. Nuttree Branch’s watershed is approximately 3,851 acres, entirely within Chesterfield County. Oldtown Creek’s watershed is approximately 8,535 acres, within Chesterfield County and the City of Colonial Heights. Proctors Creek’s watershed is approximately 12,050 acres, entirely within Chesterfield County. Rohoic Creek’s watershed is approximately 6,100 acres, within Dinwiddie County and the City of Petersburg. Swift Creek’s watershed is approximately 69,650 acres and lies within Chesterfield and Powhatan Counties.

The study watersheds include VAHU6 watersheds JA41, JA42, and portions of JA40, JL03, and JL07. Bailey Creek and Proctors Creek are direct tributaries of the James River. Oldtown Creek, Rohoic Creek, and Swift Creek are direct tributaries of the Appomattox River, and therefore indirect tributaries of the James River. Nuttree Branch is a tributary of Swift Creek, and indirectly the Appomattox River and James River. All study watersheds are tributaries of the Chesapeake Bay.

2.2. Designated Uses and Applicable Water Quality Standards

Virginia’s Water Quality Standards (9VAC25-260) consist of designated uses established for water bodies in the Commonwealth, and water quality criteria set to protect those uses. Virginia’s Water Quality Standards protect the public and environmental health of the Commonwealth and serve the purposes of the State Water Control Law (§62.1-44.2 et seq. of the Code of Virginia) and the federal Clean Water Act (33 USC §1251 et seq.).

2.2.1. Designation of Uses (9 VAC 25-260-10)

> “A. All state waters, including wetlands, are designated for the following uses: recreational uses, e.g., swimming and boating; the propagation and growth of a balanced, indigenous population of aquatic life, including game fish, which might reasonably be expected to inhabit them; wildlife; and the production of edible and marketable natural resources, e.g., fish and shellfish” (SWCB, 2011).

Bailey Creek, Nuttree Branch, Oldtown Creek, Proctors Creek, Rohoic Creek, and Swift Creek currently do not support the aquatic life designated use based on biological monitoring of the benthic macroinvertebrate community.

2.2.2. General Standard (9VAC 25-260-20)

The following general standard protects the aquatic life use:

> “A. State waters, including wetlands, shall be free from substances attributable to sewage, industrial waste, or other waste in concentrations, amounts, or combinations which contravene established standards or interfere directly or indirectly with designated uses of such water or which are inimical or harmful to human, animal, plant, or aquatic life.
>
> Specific substances to be controlled include, but are not limited to: floating debris, oil scum, and other floating materials; toxic substances (including those which bioaccumulate); substances that produce color, tastes, turbidity, odors, or settle to form sludge deposits; and substances which nourish undesirable or nuisance aquatic plant life. Effluents which tend to raise the temperature of the receiving water will also be controlled” (SWCB, 2011).

VADEQ’s biological monitoring program is used to evaluate compliance with the above standard. This program monitors the assemblage of benthic (bottom-dwelling) macro (large enough to see) invertebrates (insects, mollusks, crustaceans, and annelid worms) in streams to determine the biological health of the stream. Benthic macroinvertebrates are sensitive to water quality conditions, important links in aquatic food chains, major contributors to energy and nutrient cycling in aquatic habitats, relatively immobile, and easy to collect. These characteristics make them excellent indicators of aquatic health. Changes in water quality are reflected in changes in the structure and diversity of the benthic macroinvertebrate community. Currently, VADEQ assesses the health of the benthic macroinvertebrate community using the Virginia Stream Condition Index (VSCI). This index was first developed by Tetra Tech (2003) and later validated by VADEQ (2006). The VSCI is a multimetric index based on 8 biomonitoring metrics. The index provides a score from 0-100, and scores from individual streams are compared to a statistically derived cutoff value based on the scores of regional reference sites.

2.3. 305(b)/303(d) Water Quality Assessment

Under Section 305(b) of the Federal Clean Water Act, states are required to assess the quality of their water bodies in comparison to the applicable water quality standards. States are also required, under Section 303(d) of the Act, to prepare a list of water bodies that do not meet one or more water quality standards. This list is often called the “Impaired Waters List”, the “303(d) List”, the “TMDL List”, or even the “Dirty Waters List”. The Commonwealth of Virginia accomplishes both requirements through the publishing of an Integrated 305(b)/303(d) Water Quality Assessment Report every two years. Each report assesses water quality by evaluating monitoring data from a six-year window. The assessment window for the 2020 305(b)/303(d) Water Quality Assessment Integrated Report (IR) was from January 1, 2013 through December 31, 2018. According to VADEQ’s current Water Quality Assessment Guidance (VADEQ, 2019), streams with a calculated VSCI score ≥60 are assessed as “fully supporting” the aquatic life designated use.

Streams with VSCI scores <60 are assessed as "impaired" or "not supporting" the aquatic life designated use.

2.3.1. Impairment Listings

According to Virginia's 2020 305(b)/303(d) Integrated Report (VADEQ, 2020), Bailey Creek, Nuttree Branch, Oldtown Creek, Proctors Creek, Rohoic Creek, and Swift Creek are impaired (**Table 1-1**, **Figure 1-1**). Data collected to evaluate streams in the watersheds are collected by VADEQ and other government officials.

All study streams are impaired for failure to support the aquatic life use (i.e., a benthic impairment). These streams were initially listed as impaired on Virginia's 303(d) between 2010 and 2018 (**see Table 1-1** for stream specific listing year and station(s)). Average VSCI scores that led to each stream's listing are displayed in **Table 2-1**.

Table 2-1. Average VSCI scores used to assess stream health for all study streams

Stream	Monitoring Station	Years Sampled	Samples Collected	VSCI Average
Bailey Creek	2-BLY005.73	2010-2019	4	32
Nuttree Branch	2-NUT000.62	2010-2019	3	51.4
Oldtown Creek	2-OTC001.54	2007-2019	6	49.7
	2-OTC005.38	2015-2019	3	50.8
Proctors Creek	2-PCT002.46	2007-2019	6	51
Rohoic Creek	2-RHC000.58	2010-2019	3	48.8
Swift Creek	2-SFT019.02	2008-2009	4	48
	2-SFT019.15	2010-2019	3	43
	2-SFT025.32	2008-2019	5	44.7

2.4. TMDL Development

Section 303(d) of the Federal Clean Water Act and the U.S. Environmental Protection Agency's (USEPA) Water Quality Planning and Management Regulations (40 CFR Part 130) require states to develop Total Maximum Daily Loads (TMDLs) for waterbodies that fail to meet designated water quality standards and are placed on the state's Impaired Waters List. A TMDL reflects the total pollutant loading that a water body can receive and still meet water quality standards. A TMDL establishes the maximum allowable pollutant loading from both point and nonpoint sources for a waterbody, allocates the load among the pollutant contributors, and provides a framework for taking actions to restore water quality.

2.4.1. Pollutants of Concern

A TMDL’s target pollutants, or pollutants of concern (POC), are the physical or chemical substances that will be controlled and allocated in the TMDL to restore aquatic life (measured by benthic macroinvertebrate health). POCs must be pollutants that are controllable through source reductions, such as sediment, phosphorus, nitrogen, or other substances. Physical factors or environmental conditions, such as flow regimes, hydrologic modifications, or physical structures (like dams) cannot be TMDL POCs.

In 2021, a stressor identification analysis study was conducted to determine the POC(s) contributing to the benthic impairments in the James River Tributaries watersheds. This study is included in **Appendix D**. The stressor analysis study used a formal causal analysis approach developed by USEPA, known as CADDIS (Causal Analysis Diagnosis Decision Information System). The CADDIS approach evaluates 14 lines of evidence that support or refute each candidate stressor as the cause of impairment. In each stream, each candidate stressor was scored from -3 to +3 based on each line of evidence. Total scores across all lines of evidence were then summed to produce a stressor score that reflects the likelihood of that stressor being responsible for the impairment. The study found that sediment (measured as total suspended solids or TSS) was a probable stressor in all of the impaired tributaries. In three of the tributaries, Oldtown Creek, Rohoic Creek, and Swift Creek, an additional probable stressor of total phosphorus (TP) was identified.

3.0 WATERSHED CHARACTERIZATION

3.1. Ecoregion

Bailey Creek, Oldtown Creek, Proctors Creek, and Rohoic Creek lie entirely within the Rolling Coastal Plain USEPA ecoregion (**Figure 3-1**). Nuttree Branch lies within the Northern Outer Piedmont and Triassic Basins USEPA ecoregions. Swift Creek crosses the Northern Outer Piedmont, Rolling Coastal Plain, and Triassic Basins USEPA ecoregions. The Northern Outer Piedmont is characterized by low hills, rounded hills, and shallow ravines and is underlain by heavily weathered metamorphic rock (Woods et al., 1999). The Rolling Coastal Plain is underlain by unconsolidated tertiary sand, silt, clay, and gravels and is characterized by notably hillier terrain than adjacent coastal plain regions but is significantly flatter than the adjacent Northern Outer Piedmont ecoregion. The Triassic Basin is characterized by low rounded hills, gentle ridges, and shallow valleys and is underlain by unmetamorphosed Mesozoic rocks downfaulted into older metamorphic and igneous materials. The natural vegetation in all ecoregions would have originally consisted of a mixed oak-hickory-pine forest. Agricultural and urban and suburban development have impacted the extent of the native forest cover previously described in each ecoregion.

3.2. Soils

The soil related parameters for the watershed were derived from the Soil Survey Geographic (SSURGO) dataset (NRCS, accessed 2021). The predominant factor analyzed was the hydrologic soil group (HSG). Hydrologic soil groups are an index of the rate at which water infiltrates through the soil with group A having the greatest rate of infiltration and D having the lowest rate of infiltration. The dual groups (A/D, B/D, and C/D) indicate a naturally slow infiltration rate due to high water table, rather than a lack of infiltration capacity. When rainfall amounts exceed the capacity of the soil to infiltrate water, the excess water runs off and contributes to erosion.

Nuttree Branch, and Swift Creek watersheds are dominated by HSG B with significant contribution of group D. Bailey Creek watershed is also dominated by group B with significant inclusion of dual group B/D. Rohoic Creek is highly dominated by group C soils. Oldtown and Proctors Creek watersheds are mosaiced by a dominance of group D and dual groups, all indicating slower infiltration as expected. The spatial distribution of soil groups can be seen in **Figure 3-2**.

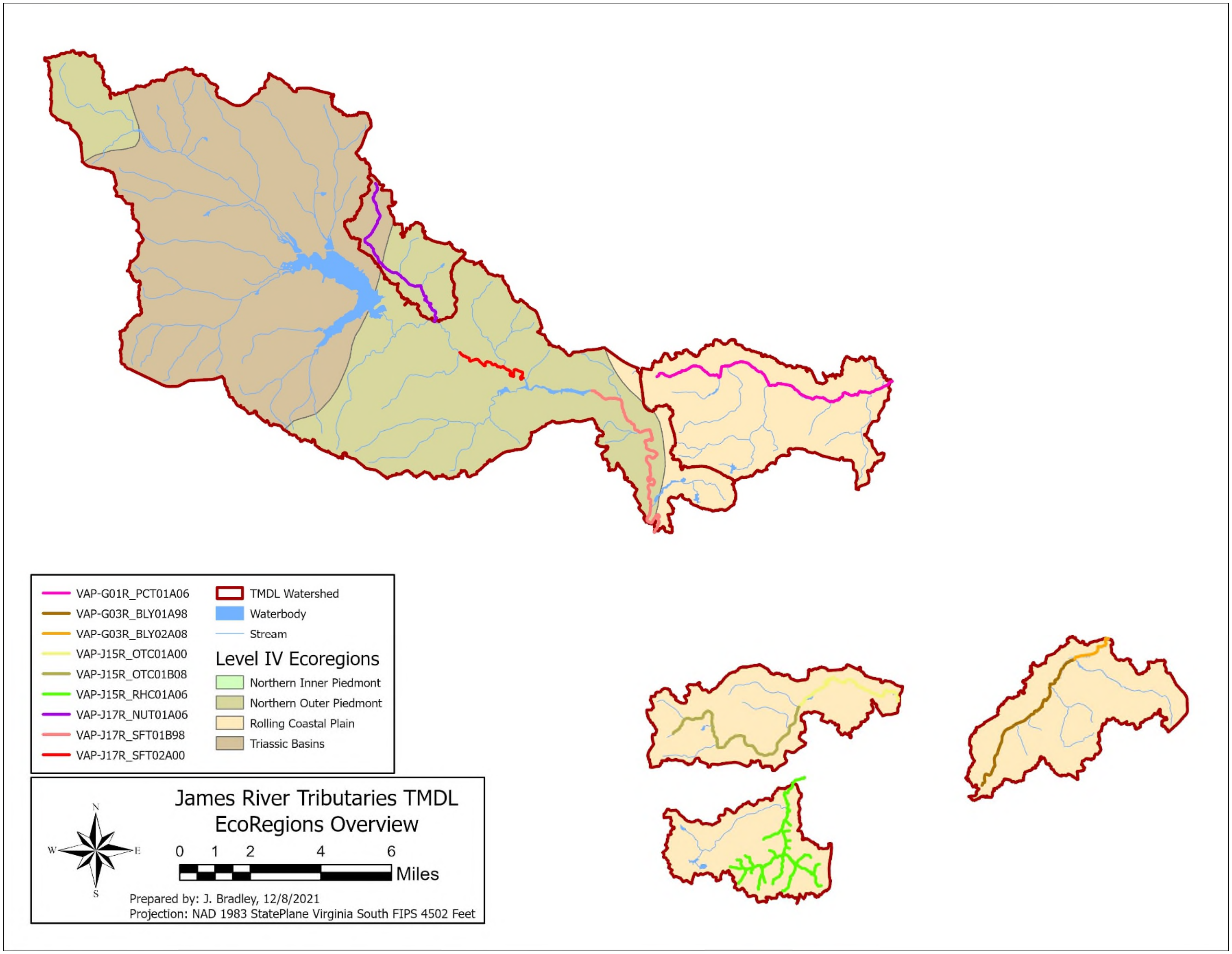

Figure 3-1. USEPA ecoregions included in the James River tributaries TMDL watersheds.

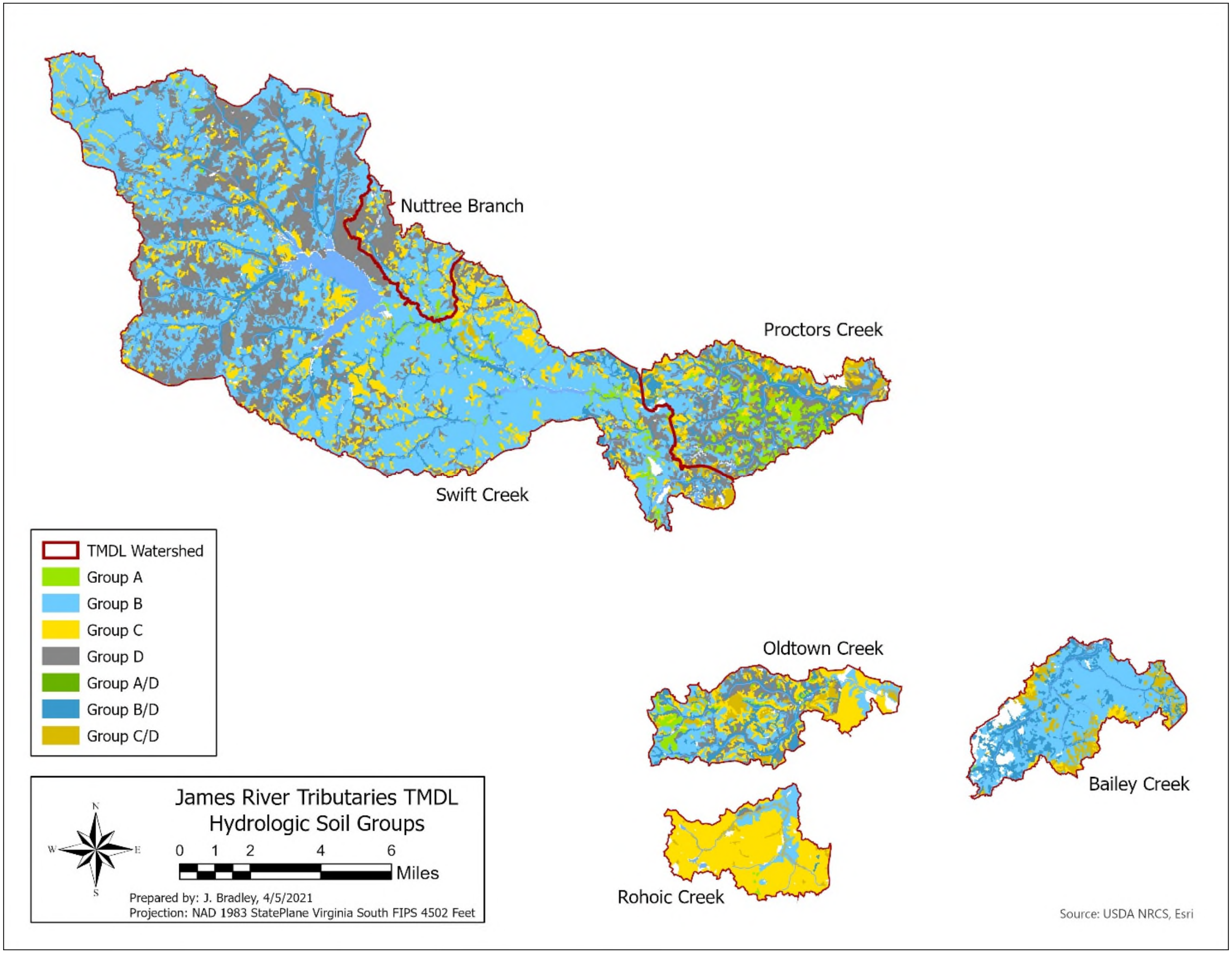

Figure 3-2. SSURGO hydrologic soil groups throughout the James River tributaries watersheds.

3.3. Climate

Daily rainfall and temperature data for the watershed was obtained from Oregon State's spatially distributed PRISM model (Parameter-Elevation Regressions on Independent Slopes Model), which interpolates available datasets from a range of monitoring networks and is used as the official spatial climate data sets of the USDA. PRISM was utilized to obtain a more exact estimate of historical weather within the watershed, rather than relying on a nearby gauge outside of the watershed (PRISM, 2021). See Daly et al. 2008 for more information on the PRISM model. Local annual average precipitation generated from the PRISM model for years 2000 to 2021 was 47.0 inches, and the average modelled daily temperature during this time range was 57.2^{o} F.

3.4. Land Cover/Land Use

The 2016 VGIN land cover dataset was used to determine the land cover distribution throughout the watershed (**Figure 3-3**). **Table 3-1** through **Table 3-6** summarize the land cover distributions for each of the impaired watersheds.

The VGIN dataset contains two different types of impervious land cover: extracted and local datasets. The local dataset's impervious land cover is based on locally developed datasets covering specifically building footprints, roads, and other known impervious areas. This land cover type is included in the computer model as entirely impervious. VGIN's extracted impervious land cover layer was developed using computer algorithms to extract additional areas that are likely impervious, beyond those areas identified in local datasets. When compared with aerial imagery, the extracted land cover set includes some areas that are not impervious. Based on visual comparisons, the extracted impervious land cover layer from VGIN was treated in the model as 80% developed impervious and 20% developed pervious. The 'NWI/other' land cover type in the VGIN dataset is based on the combined National Wetlands Inventory and Tidal Marsh Inventory datasets and represents all identified wetland areas in those datasets. The VGIN dataset contains categories for cropland and pasture, which were subdivided for modeling purposes using the 2020 Nonpoint Source (NPS) Assessment Land Use/Land Cover database maintained by the Virginia Department of Conservation and Recreation (VADCR) (VADCR, 2020). The VADCR NPS land use database includes acreage estimates by county and by VAHU6 watersheds for acres of land in conventional and conservation tillage as well as hay and three quality-based categories of pasture. The ratio of conventional to conservation tillage for each modelled subwatershed was used to divide the VGIN cropland acres for that subwatershed into acreages of high till and low till, which were simulated using appropriately different parameters within the model, such as curve number, cover management (C) factor, and practice (P) factor. The VGIN pasture acres for each subwatershed were divided into four categories based on the NPS database: hay, pasture-good, pasture-fair, and pasture-poor. These categories were simulated with appropriately different curve number and C-factor values.

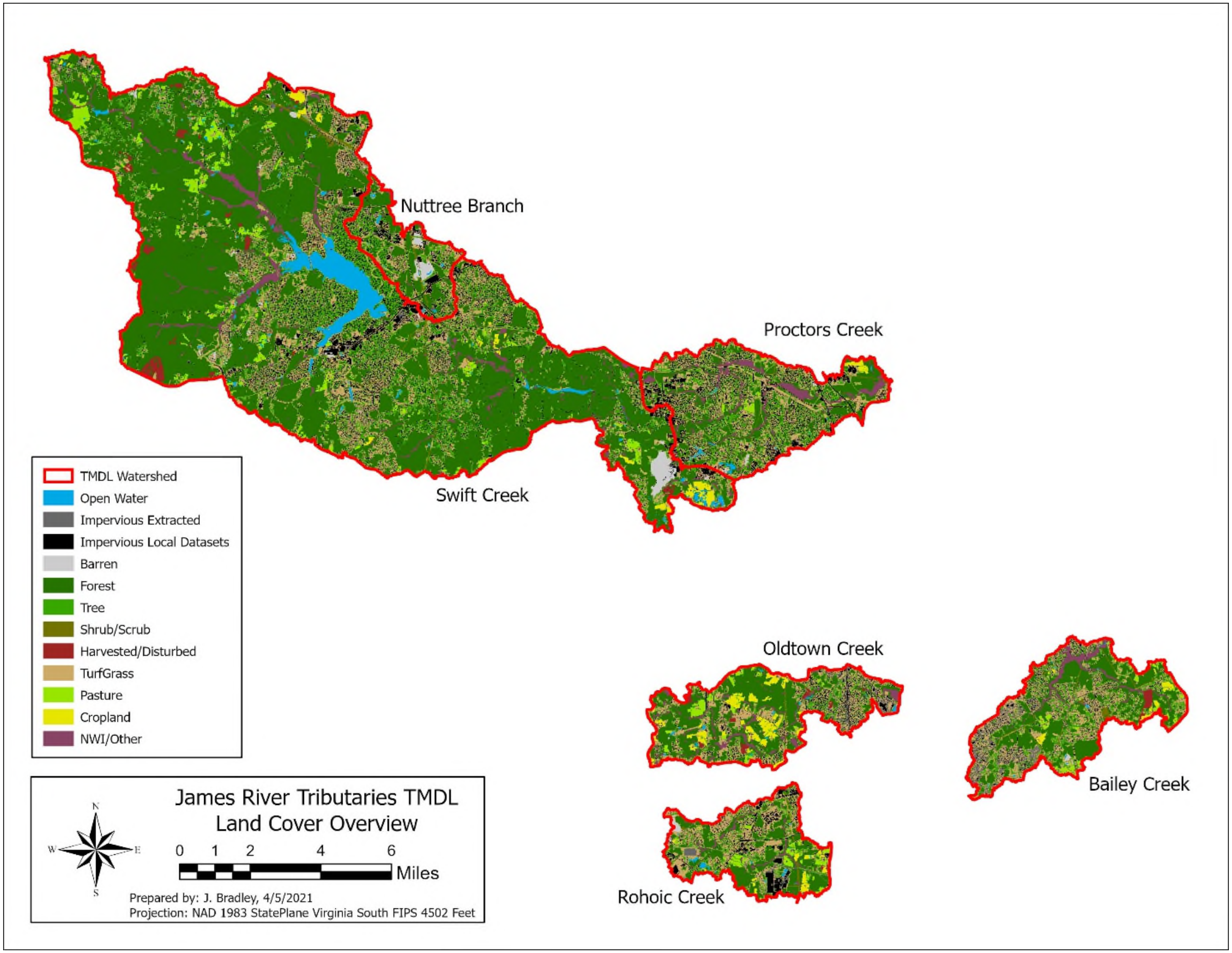

Figure 3-3. Land cover distribution used in the James River tributary watershed models.

Table 3-1. Land cover distribution in the Bailey Creek watershed.

Bailey Creek Watershed		
Land Cover Category	**Acres**	**Percentage**
Cropland	138	1.5
Hay	200	2.2
Pasture	12	0.1
Forest	2719	29.8
Trees	1502	16.5
Shrub	132	1.4
Harvested/ Disturbed	89	1.0
Water	17	0.2
Wetland	412	4.5
Barren	18	0.2
Turfgrass	2378	26.1
Developed, pervious	199	2.2
Developed, impervious	1304	14.3
Total	*9,118*	*100*

Table 3-2. Land cover distribution in the Nuttree Branch watershed.*

Nuttree Branch Watershed		
Land Cover Category	**Acres**	**Percentage**
Cropland	-	0.0
Hay	-	0.0
Pasture	-	0.0
Forest	1033	27.7
Trees	829	22.2
Shrub	39	1.0
Harvested/ Disturbed	-	0.0
Water	42	1.1
Wetland	29	0.8
Barren*	-	0.0
Turfgrass	952	25.5
Developed, pervious	32	0.9
Developed, impervious	773	20.7
Total	*3,728*	*100*

*Quarry area removed from barren land cover as it doesn't drain to stream and is accounted for in permits, total watershed area varies slightly from previously reported values for this reason.

Table 3-3. Land cover distribution in the Oldtown Creek watershed.

Oldtown Creek Watershed		
Land Cover Category	**Acres**	**Percentage**
Cropland	627	7.3
Hay	2410	2.8
Pasture	2	0.0
Forest	2,805	32.9
Trees	998	11.7
Shrub	31	0.4
Harvested/ Disturbed	135	1.6
Water	59	0.7
Wetland	502	5.9
Barren	2	0.0
Turfgrass	1,998	23.4
Developed, pervious	100	1.2
Developed, impervious	1,0356	12.1
Total	*8,535*	*100*

Table 3-4. Land cover distribution in the Proctors Creek watershed.

Proctors Creek Watershed		
Land Cover Category	**Acres**	**Percentage**
Cropland	76	0.6
Hay	63	0.5
Pasture	7	0.1
Forest	2,419	20.1
Trees	2,410	20.0
Shrub	71	0.6
Harvested/ Disturbed	-	0.0
Water	83	0.7
Wetland	806	6.7
Barren	44	0.4
Turfgrass	3,467	28.8
Developed, pervious	90	0.7
Developed, impervious	2,513	20.9
Total	*12,050*	*100*

Table 3-5. Land cover distribution in the Rohoic Creek watershed.*

Rohoic Creek Watershed		
Land Cover Category	**Acres**	**Percentage**
Cropland	60	2.4
Hay	110	4.5
Pasture	1	0.0
Forest	703	28.8
Trees	341	13.9
Shrub	24	1.0
Harvested/ Disturbed	7	0.3
Water	23	0.9
Wetland	76	3.1
Barren*	-	0.0
Turfgrass	673	27.5
Developed, pervious	28	1.2
Developed, impervious	398	16.3
Total	*2,444*	*100*

Table 3-6. Land cover distribution in the Swift Creek watershed.*

Swift Creek Watershed		
Land Cover Category	**Acres**	**Percentage**
Cropland	460	0.7
Hay	1,212	1.7
Pasture	519	0.7
Forest	34,859	50.2
Trees	9,855	14.2
Shrub	296	0.4
Harvested/ Disturbed	476	0.7
Water	2,051	3.0
Wetland	1,901	2.7
Barren*	152	0.2
Turfgrass	10,326	14.9
Developed, pervious	435	0.6
Developed, impervious	6,879	9.9
Total	*69,424*	*100*

*Quarry area removed from barren land cover as it doesn’t drain to stream and is accounted for in permits, total watershed area varies slightly from previously reported values for this reason.

3.5. Water Quality and Biological Monitoring Data

Biological, physical, and chemical data from 48 monitoring stations within the TMDL watersheds were used in developing the stressor analysis study. All monitoring stations provided water quality data, and 14 stations provided benthic data (the 14 benthic stations were co-located with water quality stations). The data from these monitoring stations are explored in the attached stressor identification analysis study (**Appendix D**) and benthic stations are summarized in **Table 3-7**. The various benthic monitoring stations are shown in **Figure 3-4.**

Table 3-7. Summary of benthic data collected in the study watersheds.

TMDL Watershed	Benthic Station ID	Location	Year(s) Sampled
Bailey Creek	2-BLY005.73	Downstream of Rt. 630	2010-2019
Nuttree Branch	2-NUT000.62	500m downstream of Rt 630	2010-2019
Oldtown Creek	2-OTC001.54	Just upstream of Conduit Rd	2007-2019
Oldtown Creek	2-OTC005.38	Upstream of Rt 628	2015-2019
Proctors Creek	2-PCT002.46	Rt 1 bridge	2007-2019
Rohoic Creek	2-RHC000.58	50m downstream of Rt 460	2010-2019
Swift Creek	2-SFT012.84	Rt. 631 bridge, just upstream from Bradley Bridge gauging station 02042000	2014
Swift Creek	2-SFT019.02	1 mile downstream of Rt 655	2008-2009
Swift Creek	2-SFT019.15	Upstream of SR 655	2010-2019
Swift Creek	2-SFT025.32	Just upstream of Rt 653 bridge	2008-2019
Swift Creek	2-HEP001.27	Horsepen Creek above Rt 667	2002
Swift Creek	2-LIA000.50	Licking Creek at Rt 5186 below Second Br	2008
Swift Creek	2DOTD002.52	Otterdale Branch 100 m upstream of Clover Hill Athletic Complex Road	2011
Swift Creek	2DTRO001.88	Third Branch 600m downstream of Rt 654	2011

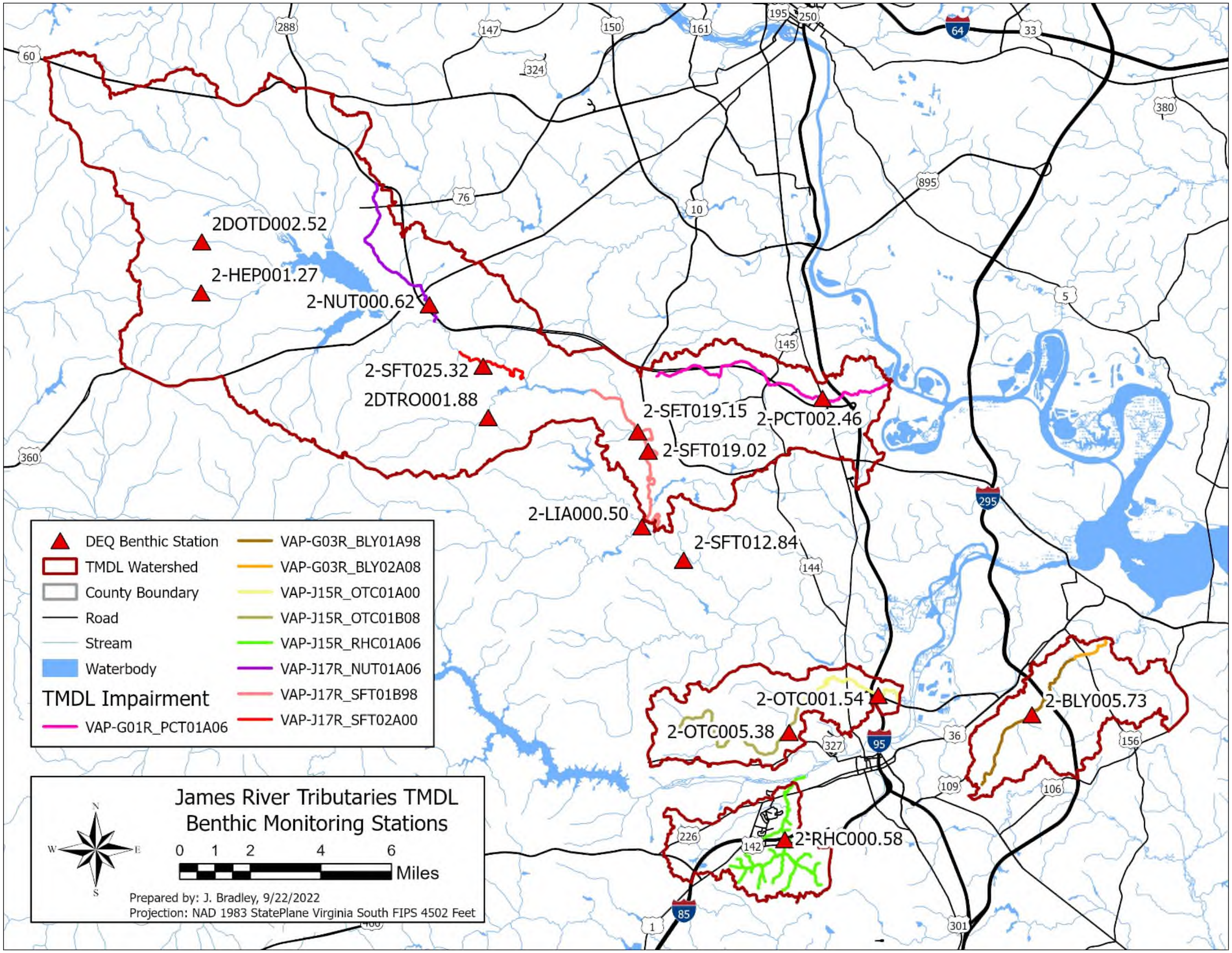

Figure 3-4. Locations of VADEQ benthic monitoring stations in the James River tributaries watersheds.

4.0 MODELING PROCESS

A computer numerical model was used in this study to simulate the relationship between pollutant loadings and in-stream water quality conditions.

4.1. Model Selection and Description

The model selected for development of the sediment and phosphorus TMDLs in the James River Tributaries TMDL was the Generalized Watershed Loading Functions (GWLF) model, developed by Haith et al. (1992), with modifications by Evans et al. (2001), Yagow et al. (2002), and Yagow and Hession (2007). GWLF is based on loading functions, which are a compromise between the empiricism of export coefficients and the complexity and data-intensive nature of process-based simulations (Haith et al., 1992). GWLF operates in metric units, but outputs were converted to English units for this report.

GWLF is a continuous simulation model that operates on a daily timestep for water balance calculations and outputs monthly runoff, sediment, and nutrient yields for the watershed. The model allows for multiple land cover categories to be incorporated, but spatially it is lumped because it does not account for the spatial distribution of sources and has no method of spatially routing sources within the watershed.

Observed daily precipitation and temperature data is input, along with land cover distribution and a range of land cover parameters, which the model uses to estimate runoff and sediment loads in addition to dissolved and attached nitrogen and phosphorus loads. Surface runoff is calculated using the Soil Conservation Service Curve Number (SCS-CN) approach. Curve numbers are a function of soils and land use type. Erosion is calculated in GWLF based on the Universal Soil Loss Equation (USLE). USLE incorporates the erosivity of rainfall in the watershed area, inherent erodibility of the soils, length and steepness of slopes, as well as factors for cover and conservation practices that affect the impact of rainfall and runoff on the landscape. Impervious or urban sediment inputs are calculated in GWLF with exponential accumulation and washoff functions. GWLF incorporates a delivery ratio into the overall sediment supply to estimate sediment deposition before runoff carries it to a stream segment. GWLF's sediment transport algorithm takes into consideration the transport capacity of the runoff based on calculated runoff volume.

Stream bank and channel erosion is calculated using an algorithm by Evans et al. (2003) as incorporated in the AVGWLF version (Evans et al., 2001) of the GWLF model and corrected for a flow accumulation coding error (VADEQ, 2005). This algorithm incorporates the stream flow, fraction of developed land (i.e. impervious cover) in the watershed, and livestock density in the watershed with the area-weighted curve number and soil erodibility factors and the mean slope of the watershed.

Groundwater discharge to the stream is calculated using a lumped parameter for unsaturated and shallow saturated water zones throughout the watershed. Infiltration to the unsaturated zone occurs when precipitation exceeds surface runoff and evapotranspiration. Percolation from the unsaturated zone to the shallow saturated zone occurs when the unsaturated zone capacity is exceeded. The shallow saturated zone contributes groundwater discharge to the stream based on a recession coefficient, and groundwater loss to a deep saturated zone can be modeled using a seepage coefficient.

Surface nutrient losses are determined by applying dissolved nitrogen and phosphorus coefficients to surface runoff and a nutrient content coefficient to the sediment yield for pervious source areas. Impervious or urban nutrient inputs are calculated with exponential accumulation and washoff functions. GWLF also includes functionality for manure applications and septic systems.

4.2. Model Setup

Watershed data needed to run GWLF were generated using spatial data, water quality monitoring data, streamflow data, local weather data, literature values, stakeholder input, and best professional judgement. In general, the GWLF manual (Haith et al., 1992) served as the primary source of guidance in developing input parameters where newer published methods were not available. Values for the various GWLF input parameters for each model are detailed in **Appendix A**. A sensitivity analysis of the model to select parameters is presented in **Appendix B**.

Local weather data (spanning from April 1, 2000 to March 31, 2021), including daily rainfall totals and average daily temperature, was obtained from the PRISM climate model (PRISM, 2021). The PRISM model incorporates climate observations from a variety of sources, applies quality control measures, and develops spatial climate datasets incorporating DEM models to improve model accuracy. Daily weather was modelled at Fine Creek Mills (37.5838, -77.8907), near USGS gage #02036500, which was used for model calibration (see **Section 4.5**).

The model allows for multiple land cover categories to be incorporated, but spatially it is lumped, meaning that it does not account for the spatial distribution of sources within the watershed. The standard practice is to sub-divide larger watersheds into smaller subwatersheds that can be simulated individually to get a more granular assessment of the pollutant loads. The TMDL study area was divided into 26 subwatersheds. The Swift Creek study area was divided into subwatersheds one through sixteen, with subwatershed nine being the Nuttree Branch study. The Proctors Creek and Bailey Creek watersheds were each divided into three subwatersheds, while the Oldtown Creek and Rohoic Creek watersheds were each divided into two subwatersheds (**Figure 4-1**). Locations of monitoring stations were used to guide subwatershed development to take advantage of available data. Junctions of streams were also used as breaking points to reduce subwatershed size, allowing large tributaries to be modeled independently.

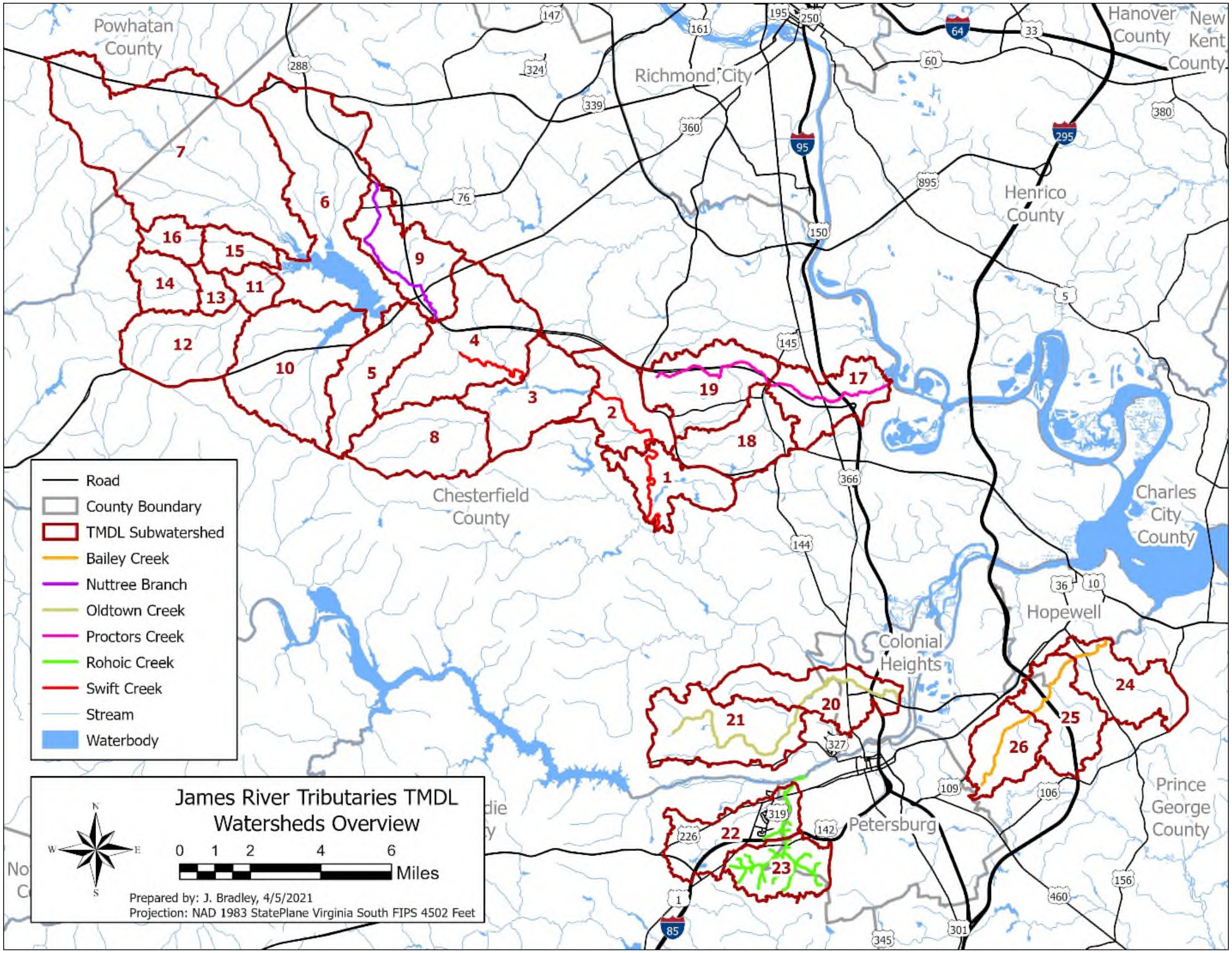

Figure 4-1. James River tributaries TMDL model subwatersheds.

4.3. Source Assessment

Sediment and phosphorus can be delivered to streams by either point or non-point sources. Point sources include permitted sources such as water treatment facilities. Non-point sources encompass all of the other sources in the watersheds. Non-point sediment and phosphorus is primarily from surface runoff (that is not captured and converted to point sources) and erosion happening within and on the banks of streams. Phosphorus in particular can be either bound to and transported with eroded sediment or dissolved in water directly.

4.3.1. Non-Point Sources

4.3.1.1. Surface Runoff

Sediment and attached phosphorus can be transported from both pervious and impervious surfaces during runoff events. Between rainfall events, sediment accumulates on impervious surfaces and can then be washed off during runoff events. On pervious surfaces, soil particles are detached by rainfall impact and shear stress from overland flow and then transported with the runoff water to nearby streams. Various factors including rainfall intensity, storm duration, surface cover, topography, tillage practices, soil erosivity, soil permeability, and other factors all impact these processes. Surface applications of manure and other fertilizers are also subject to suspension and transport via runoff. In addition to the phosphorus attached to mobilized sediment particles, phosphorus can also be dissolved in water. Surface runoff can 'pick up' soluble phosphorus and then contribute directly to dissolved phosphorus in streams.

The VGIN 2016 land cover dataset was used to determine the distribution of different land cover types in the watersheds (with the modifications noted in **Section 3.3**). Values for various parameters affecting sediment and phosphorus loads were gleaned from literature guidance (CBP, 1998; Haith et al., 1992; Hession et al., 1997, CTBMPEP, 2016, SSDCEP, 2015).

4.3.1.2. Streambank Erosion

Sediment is transported in stream systems as part of their natural processes. However, changes to the landscape can alter these processes, in turn changing the balance of sediment mobilization and deposition within the stream system. Phosphorus in the soil binds tightly with sediment and is transported in the stream along with the associated sediment, altering the loading and transportation of phosphorus within the watershed.

Increases in impervious areas can increase the amount and rate of flow in streams following rainfall events, which provides more erosive power to the streams and increases the channel erosion potential. This is often the cause of the entrenchment, or downcutting, of urban streams – disconnecting higher flow events from the surrounding floodplain. The higher flows are then increasingly confined to the channel, thus mobilizing more sediment, both as total suspended sediment (TSS) in the water column and bedload (the movement of larger particles along the bottom of the channel). Erosion of entrenched streams continues as steep banks are more susceptible to erosion and eventually mass wasting as chunks of undercut banks are dislodged into the stream. Sediment deposition between storm events and the highly mobile bed material during erosive storm flows negatively impact aquatic life.

Additionally, impacts to riparian (streambank) vegetation from livestock access and other management practices weaken the stability of the streambanks themselves as root system matrices break down. Weakened streambanks are more easily eroded by storm flows and can lead to excessive channel migration and eventual channel over-widening. Increasing channel width decreases stream depth which can lead to increased sediment deposition and increased water temperatures, which both negatively impact aquatic life.

Stream bank and channel erosion is calculated in GWLF using an algorithm by Evans et al. (2003) as incorporated in the AVGWLF version (Evans et al., 2001) of the GWLF model and corrected for a flow accumulation coding error (VADEQ, 2005). This algorithm estimates average annual streambank erosion as a function of cumulative stream flow, fraction of developed land (i.e. impervious cover) in the watershed, and livestock density in the watershed with the area-weighted curve number and soil erodibility factors and the mean slope of the watershed.

4.3.1.3. Groundwater

Shallow surface groundwater interacts with phosphorus both dissolved in percolating runoff and attached to the soil itself. The higher the concentration of soil-bound phosphorus and dissolved phosphorus in runoff water, the higher the levels of phosphorus in shallow groundwater. Groundwater can contribute directly to streamflow through upwelling, taking its dissolved phosphorus with it and adding to the overall total phosphorus (TP) load in the streams.

4.3.1.4. Residential Septic Systems

Residential septic systems are designed so that their drainfields dissipate effluent over a broad area. The organic phosphorus in the effluent is adsorbed to soil particles and used by plants and microorganisms. When systems are failing, they can discharge nutrient-rich waste to the surface instead, where it is easily transported to surface waters during runoff events, or directly to surface waters if nearby.

The number and distribution of dwellings with septic systems throughout the watersheds was determined using a dataset provided by Virginia Department of Health dated March 2021 (**Table 4-1**). Residences with failing (ponded) septic systems were estimated based on a failure rate of 3.3% (except 0.51% in Chesterfield County, failure rate provided by county), derived from the assumption that each septic system fails, on average, once during an expected lifetime of 30 years. Without reliable estimates or stakeholder input stating otherwise, it was assumed that there were no direct sewage discharges to streams (straight pipes). Census data (US Census Bureau, 2020) for the localities was used as the reference for number of persons per household, which was applied to the number of residences on septic systems to obtain a population distribution to be input to GWLF.

Table 4-1. Estimated numbers of residences with septic systems.

TMDL Watershed	Sub-watershed	Percent Failure Rate	Functioning Septic Systems	Ponded Septic Systems
Swift Creek	1	0.51	294	2
	2	0.51	79	0
	3	0.51	15	0
	4	0.51	130	1
	5	0.51	21	0
	6	0.51	40	0
	7	0.51	199	1
	8	0.51	507	3
Nuttree Branch (within Swift Creek)	9	0.51	15	0
Swift Creek	10	0.51	31	0
	11	0.51	4	0
	12	0.51	11	0
	13	0.51	5	0
	14	0.51	2	0
	15	0.51	12	0
	16	0.51	8	0
Proctors Creek	17	0.51	66	0
	18	0.51	109	1
	19	0.51	50	0
Oldtown Creek	20	0.51	21	0
	21	0.51	55	0
Rohoic Creek	22	3.30	2	0
	23	3.30	6	0
Bailey Creek	24	3.30	17	0
	25	3.30	16	0
	26	3.30	3	0

4.3.2. Point Sources

Various point sources of sediment and phosphorus exist within the James River tributaries watersheds. These point sources are permitted under the Virginia Pollutant Discharge Elimination System (VPDES) program and include the following categories of permits: individual permits, non-metallic mineral mining (NMMM) general permits, concrete facility general permits, industrial stormwater (ISW) general permits, vehicle wash / laundry facility general permits, domestic sewage general permits, municipal separate storm sewer system (MS4) permits, and construction stormwater general permits. The approach for determining pollutant loads from each of these permit types is described below. Typically, wasteload allocations for VPDES general permits in a TMDL are aggregated by permit type (if multiple of the same permit type). As permits are issued in the watershed in the future, the associated loads will be aggregated within the relevant TMDL wasteload allocation.

4.3.2.1. VPDES Individual Permit

There are three VPDES individual permits within the study area, associated with a correctional center, Fort Lee, and a water treatment facility. The existing condition's sediment and phosphorus loads from the facilities were calculated from discharge monitoring report data. The existing conditions load for the Addison Evans Water facility was set to zero, as there has been no record of discharge in the last thirty years, though the permit is still valid. The permitted loads, which are included in the wasteload allocation of the TMDL, were calculated based on the permitted discharge and concentration for each facility (**Table 4-2**).

Table 4-2. Sediment and phosphorus loads associated with VPDES individual permits.

Permit Number (Facility Name)	Receiving Stream	Permitted Discharge (MGD)	Permit Conc. (mg/L TSS)	Allocated Load (lb/yr TSS)	Permit Conc. (mg/L TP)	Allocated Load (lb/yr TP)
VA0023426 (DOC Central Virginia Correctional Center for Women)	Swift Creek	0.065	45	8,910	0.23	46
VA0059161 (US Army Garrison Fort Lee, outfall #002)	Bailey Creek	0.046	30	4,204	n/a*	n/a*
VA0006254 (Addison Evans Water Production Laboratory)	Swift Creek	0.5	60	91,382	0.23	9.6

*Bailey Creek not subject to phosphorus TMDL

4.3.2.2. Nonmetallic Mineral Mining General Permit

There are three nonmetallic mineral mining (NMMM) general permits in the watershed (**Table 4-3**). These facilities are permitted sources of sediment at an average concentration of 30 mg/L TSS. Discharge rates were calculated based on provided DMR data. There is currently no permitted loading rate for phosphorus in the NMMM general permit. As such, VADEQ developed a methodology to estimate the loads from these permits using the Chesapeake Bay TMDL Phase III Watershed Implementation Plan (WIP) Input Deck Process Water Assumptions based on various categories of VPDES general permits. For VAG84 – Nonmetallic Mineral Mining permits an average TP concentration of 0.02 mg/L TP is listed in the Input Deck Assumptions. This concentration was applied to the discharge rate for each permit.

Table 4-3. Nonmetallic mineral mining general permits in the study area.

Permit Number	Facility Name	Stream	Allocated Discharge (MGD)	Allocated Load (lb/ yr TSS)	Allocated Load (lb/ yr TP)
VAG840079	Midlothian Quarry	Nuttree/ Swift	0.50	45,690.6	30.5
VAG840114	Vulcan Construction Materials LLC – Dale Quarry	Swift	1.50	137,071.8	91.4
VAG840126	Vulcan Construction Materials LLC – Jack Quarry	Rohoic	1.40	127,933.7	85.3

4.3.2.3. Concrete Products Facility General Permit

There are five concrete products facilities general permits in the study area (**Table 4-4**). These facilities are a permitted source of sediment and phosphorus in the watershed and contribute pollutants primarily from stormwater runoff. For process water (where applicable), pollutant loads from each facility were calculated using the average flow rate and permitted loading rate of 30 mg/L TSS. There is not currently a permitted loading rate for phosphorus in the concrete facilities general permit, though. As such, VADEQ developed a methodology to estimate the loads from these permits using the Chesapeake Bay TMDL Phase III Watershed Implementation Plan (WIP) Input Deck Process Water Assumptions based on various categories of VPDES general permits. For VAG11 – Concrete Products permits, an average TP concentration of 0.71 mg/L TP is listed in the Input Deck Assumptions. This concentration was applied to the average discharge rate for process water, where applicable.

Concrete facility permitted outfalls associated with only stormwater loads were handled in the same way as Industrial Stormwater Permits (**Section 0**) by using a weight per unit area loading rate to calculate loads (440 lb/ac/yr and 1.5 lb/ac/yr for sediment and phosphorus, respectively).

Table 4-4. Concrete products facility general permits in the study area.

Permit Number	Facility Name	Receiving Stream	Load Type	Allocated Load (lb/yr TSS)	Allocated Load (lb/yr TP)
VAG110157	Smyrna Ready Mix	Proctors Creek	Stormwater	1188.0	4.1
VAG110158	Mechanicsville Concrete LLC – Petersburg Ready Mix	Rohoic Creek	Stormwater	1166.0	4.0
VAG110159	Chesterfield Ready Mix Concrete Plant	Nuttree Branch	Stormwater	325.6	1.1
VAG110171	Vulcan Construction Materials LLC – Dinwiddie	Rohoic Creek	Stormwater	1592.8	5.4
			Process Water (0.01 MGD)	1827.6	21.6
VAG110231	Greenrock Materials LLC – Prince George Plant	Bailey Creek	Stormwater	1944.8	6.6

4.3.2.4. Industrial Stormwater (ISW) General Permit

There are 19 industrial stormwater (ISW) general permits in the study area (**Table 4-5**). Sediment and phosphorus loads from industrial stormwater permits are included in this study. There is currently no permitted loading rate for either sediment or phosphorus for industrial stormwater sources in the general permit. However, the Chesapeake Bay TMDL now requires permittees to assess their nutrient and sediment loadings. As such, VADEQ developed a methodology to estimate the loads from ISW permitted areas. To develop existing loads, the regulated acreages for the permits were separated from the accounting of total acreages for the watershed. Under existing conditions, the regulated industrial acres for each permit were included in the model at the same loading rate as other developed, impervious acres. In the TMDL allocation scenario, the allocated loads were calculated using the same methodology, but utilizing the loading rates of 440 lb/ac/yr TSS and 1.5 lb/ac/yr TP, as noted in the general permit. These values are cited in the permit (9VAC25-151-70) as those used to estimate the loading from industrial stormwater facilities in Chesapeake Bay TMDL documentation.

Table 4-5. Industrial stormwater general permits in the study area.

Permit Number	Facility Name	Receiving Stream
VAR050549	Kaiser Aluminum Fabricated Products LLC	Proctors Creek
VAR050583	South Side Auto Recycling Inc.	Nuttree Branch
VAR050594	US Army Garrison and Fort Lee	Bailey Creek
VAR050614	Harrells Used Auto Parts	Bailey Creek
VAR050619	Chaparral Virginia Inc.	Rohoic Creek
VAR050625	Reynolds Consumer Products LLC	Proctors Creek
VAR050666	Branscome Richmond – Chesterfield Plant	Nuttree Branch
VAR050672	Adams Construction Co. - Jack Plant	Rohoic Creek
VAR051023	Dominion Energy – Chesterfield Power Station	Proctors Creek
VAR051168	Aleris Rolled Products Inc.	Proctors Creek
VAR051218	International Paper – Petersburg	Rohoic Creek
VAR051683	Lee Hy Paving Corp – Chester	Swift Creek
VAR051684	Shoosmith Sanitary Landfill	Swift Creek
VAR051893	Atlantic Iron and Metal	Rohoic Creek
VAR052059	Hillcrest Transportation Inc.	Rohoic Creek
VAR052185	TFC Recycling – Chester Facility	Proctors Creek
VAR052263	Hill Phoenix – Battery Brooke Pkwy	Proctors Creek
VAR052314	Pierce Mechanical Inc	Proctors Creek
VAR052351	County Waste MRF	Swift Creek

4.3.2.5. Vehicle Wash Facility General Permit

There is one vehicle wash facility general permit in the watershed (**Table 4-6**). The discharge rate was based on provided permit data. Allocated sediment loads were calculated using the average discharge rate and the TSS concentration of 60 mg/L listed in the general permit. There is currently no permitted loading rate for phosphorus in the vehicle wash general permit. As such, VADEQ developed a methodology to estimate the loads from these permits using the Chesapeake Bay TMDL Phase III Watershed Implementation Plan (WIP) Input Deck Process Water Assumptions based on various categories of VPDES general permits. For VAG75 – Vehicle Wash and Laundry permits, an average TP concentration of 0.77 mg/L TP is listed in the Input Deck Assumptions. This concentration was applied to the discharge rate for each permit.

Table 4-6. Vehicle wash facility general permits in the study area.

Permit Number	Facility Name	Stream	Allocated Discharge (MGD)	Allocated Load (lb/yr TSS)	Allocated Load (lb/yr TP)
VAG750205	Chesterfield County DPR Maintenance Rinse Station	Proctors Creek	0.0003	54.8	0.7

4.3.2.6. Domestic Sewage General Permit

There are four domestic sewage general permits in the study area (**Table 4-7**). The domestic sewage general permit specifies a maximum flow rate of 1000 gallons per day at a sediment concentration of 30 mg/L. These permit limits were used to calculate a wasteload allocation of 91.44 lb/yr TSS for the domestic sewage permits in the TMDL. Using the Chesapeake Bay TMDL Phase III Watershed Implementation Plan (WIP) Input Deck Process Water Assumptions, for VAG40 – Domestic Sewage permits are listed at an average TP concentration of 7.05 mg/L TP and a flow rate of 0.0002 MGD in the Input Deck Assumptions. These values lead to a wasteload allocation of 4.30 lb/yr TP for each permit.

Table 4-7. Domestic sewage general permit in the study area.

Permit Number	Receiving Stream
VAG404275	Swift Creek
VAG404286	Swift Creek
VAG404357	Swift Creek
VAG404358	Swift Creek

4.3.2.7. Municipal Separate Storm Sewer System (MS4) Permits

There are eight MS4 permits within the TMDL watersheds (**Table 4-8**). These areas are potential sources of sediment and phosphorus to the study watersheds and were assigned wasteload allocations in this TMDL report. The existing loads were based on the extent and type of land cover within the boundaries of the permitted areas and the existing modeled loading rates associated. For the allocated loads, the same reductions by land cover were applied to the MS4 areas as recommended throughout the watershed. Due to the localized extent and interconnected nature of the permitted areas, the loads associated with the MS4 permits were aggregated and presented as one combined wasteload allocation in the final TMDL scenarios to provide some degree of flexibility to permit holders to determine their portion of the load and to address the needed reductions.

Table 4-8. MS4 permits within the watersheds.

Permit Number	Permitted Entity
VAR040006	Central State Hospital
VAR040007	Fort Lee
VAR040009	City of Colonial Heights
VAR040013	City of Petersburg
VAR040015	City of Hopewell
VAR040110	John Tyler Community College
VA0088609	Chesterfield County
VA0092975	VDOT

4.3.2.8. Construction Stormwater General Permit

There were 175 active Virginia Stormwater Management Program (VSMP) permits for construction within the watersheds at the time of TMDL development (**Table 4-9**). These permits are a potential source of sediment and phosphorus to the James River tributaries watersheds and were assigned wasteload allocations in the TMDL. Each permit contains an estimate of the permitted disturbed area, however, this area is generally not disturbed for the entire length of the permit's active status. To account for this discrepancy, the acreage estimated to be disturbed for each permit was divided over the length of the permit's active status (no less than one year). Any active permits in process of termination were excluded because at that stage in the permitting cycle all areas are stabilized.

Table 4-9. Disturbed acreage associated with active construction general permits within the watersheds.

Receiving Stream	Estimated Potential Disturbed Area (ac)
Bailey Creek	16.7
Nuttree Branch	64.4
Oldtown Creek	40.2
Proctors Creek	185.6
Rohoic Creek	64.9
Swift Creek	717.4

Disturbed acreage associated with construction permits was modeled as barren land cover, and the acres allocated to construction permits subtracted proportionally from all land cover values in the watershed so that areas were not double counted when developing the existing load estimates. Appropriate erosion and sediment control measures were assumed to be utilized on all construction projects, and for developing final WLAs for the allocation scenarios, loads were simulated with an 85% sediment removal efficacy based on Chesapeake Bay Expert Panel Guidance (ESCEP, 2014). These reductions were applied only to sediment loads, as the guidance does not indicate an effectiveness for nutrient removal by the assumed erosion control measures.

4.4. Best Management Practices

Many entities and private citizens have installed best management practices (BMPs) throughout the watersheds. Some BMPs have associated removal efficacies defined in the literature, which can be applied to the raw pollutant accumulation loads for the land areas draining to the BMP. Other BMPs can be simulated as a change in land use over the treated acreage, such as planting a riparian buffer and turning previous pasture land into forested areas. The active BMPs installed in the study watersheds included in the model are detailed in **Table 4-10**. The Chesapeake Bay Phase 5.3 Community Model Documentation Section 6 (USEPA, 2010) was used to guide the TSS and TP removal estimates.

Table 4-10. BMPs installed in the TMDL study area.

Receiving Stream	Practice	Count	Extent Installed	Efficacy method (fraction removal, other)	TSS Removed (lb/yr)	TP Removed (lb/yr)
Swift Creek	Afforestation of Crop, Hay and Pasture Land (FR-1)	2	13 ac	Land cover change	3757	23.2
	Grazing Land Management (SL-9)	2	8 ac	0.3 TSS; 0.24 TP	716	3.4
	Stream Exclusion with Grazing Land Management (SL-6)	1	50 ac	0.4 TSS; 0.3 TP	5966	26.9

4.5. Flow Calibration

GWLF was originally developed as a planning tool for estimating nutrient and sediment loadings in ungauged watersheds and was designed to be implemented without calibration. Hydrologic calibration was still performed as a preliminary modeling step to ensure that hydrology was being simulated as accurately as feasibly possible.

Historic daily flow data was available from USGS flow gauge #02036500 – Fine Creek at Fine Creek Mills back to 1990. While not located directly on one of the TMDL streams, the gauge is located on nearby Fine Creek, which was included in the development of the AllForX regression (**Section 5.0** and **8.0Appendix C**, Fine Creek watershed contains station 2-FIN000.81 noted in **Table C-1**). Fine Creek watershed is similar in size to the Proctors Creek watershed, with similar land cover distributions to the study areas, and is very close geographically. While the cumulative Swift Creek watershed is significantly larger than Fine Creek, its various subwatersheds are similarly sized. For these reasons, it is likely that the study watersheds will have a hydrologic response very similar to that of Fine Creek. Final calibrated parameters were applied to the other modeled watersheds. Local weather data, including daily rainfall totals and average daily temperature, was obtained from the PRISM climate model (see **Section 3.3**). Leaving a 'warm-up' period for the model, the years from 2011 to 2021 were used as the calibration period, and 2001 to 2010 were used as a validation dataset. These ranges are sufficiently long that a range of both dry and wet years are encompassed in each to get a good assessment of the model's performance.

Calibration efforts focused on adjusting watershed scale parameters, such as the recession coefficient, seepage coefficient, and leakage coefficient, which cannot be calculated or estimated reliably from available guidance. The typical target ranges for GWLF calibration efforts are to achieve ±5% of the observed total flow and ±20% compared to seasonal flow totals. While calibration efforts make a best effort at meeting the target for all criteria, this is not always possible as no model is a perfect simulation of the reality it is approximating. The final GWLF calibration results are shown in **Figure 4-2** and **Figure 4-3** and summarized in **Table 4-11**. The results of the calibration were also assessed for overall correlation by calculating an R^2 value for the datasets. Generally, for GWLF, an R^2 value greater than 0.7 indicates a strong positive correlation between simulated and observed data. Following calibration, the model output was run compared to the observed 2001-2010 discharge as a validation of the model calibration. The final GWLF validation results are summarized in **Table 4-11** and shown in **Figure 4-4** and **Figure 4-5**. Both the calibration and validation runs meet all of the target criteria to be considered a good fit to the observed hydrologic data.

Table 4-11. Results of hydrology calibration of GWLF model.

Criteria	Calibration Range Percent Difference (%)	Validation Range Percent Difference (%)	Entire Modelled Range (%)
Total Cumulative Discharge	6.68	-4.07	1.34
Spring Discharge	-0.18	-18.42	-8.49
Summer Discharge	-0.23	2.23	1.14
Fall Discharge	11.43	7.29	9.34
Winter Discharge	10.59	-8.11	1.41
R^2	0.80	0.82	0.81

4.6. Consideration of Critical Conditions and Seasonal Variations

The GWLF model simulated a 20-year period (2001 through 2021) with an additional buffer period of nine months at the beginning of the run serving as a ‘warm-up’ period for the model to equilibrate and minimize the impact of uncertain initial conditions. Using this extended modeling period allows the results to account for both annual and seasonal variations in hydrology and sediment and phosphorus loads.

The modeled time period encompasses a range of weather conditions for the area, including ‘dry’, ‘normal’, and ‘wet’ years, which allows the model to represent critical conditions during both low and high flows. Critical conditions during low flows are generally associated with point source loads, while critical conditions during high flows are generally associated with nonpoint source loads.

GWLF considers seasonal variation through several mechanisms. Daily time steps are used for weather data inputs and water balance equation calculations. GWLF also incorporates parameters that vary by month, including evapotranspiration cover coefficients and average hours per day of daylight. Additionally, the values for the rainfall erosivity coefficient are dependent on whether a given month is tagged as part of the growing season or dormant season. The model is also capable of incorporating data for the land-application of manure in up to two user-set application periods.

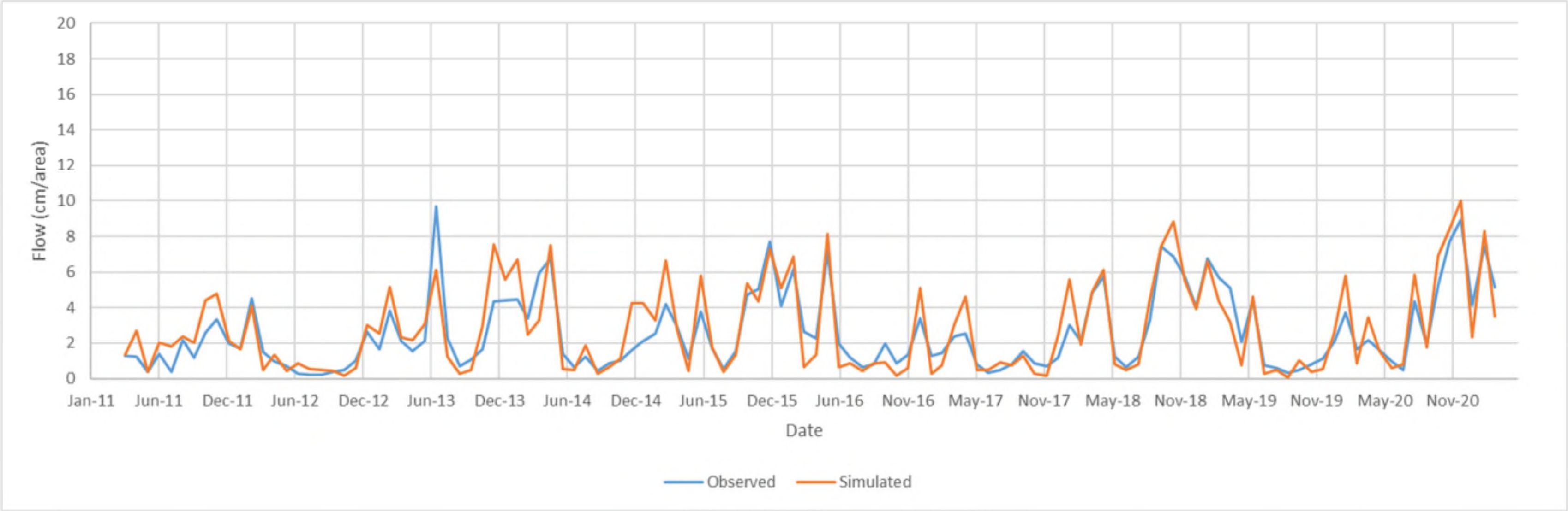

Figure 4-2. Calibration data set of simulated stream flow compared to observed flow (USGS#02036500).

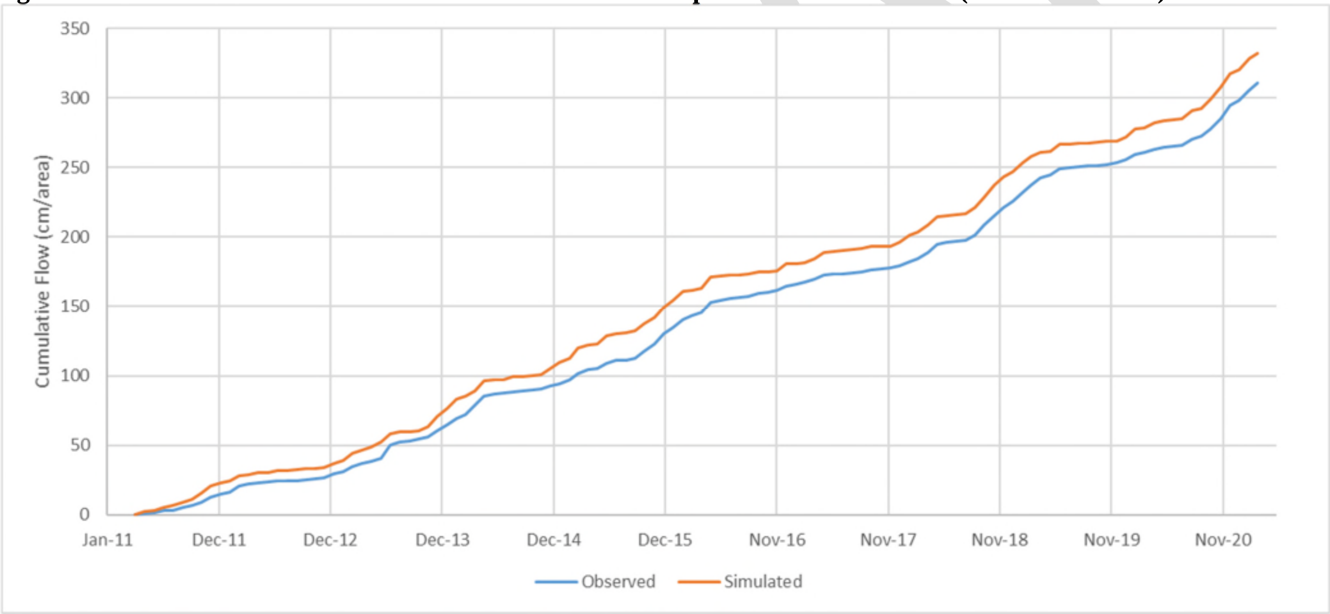

Figure 4-3. Calibration data set simulated cumulative flow from model compared to observed (USGS#02036500).

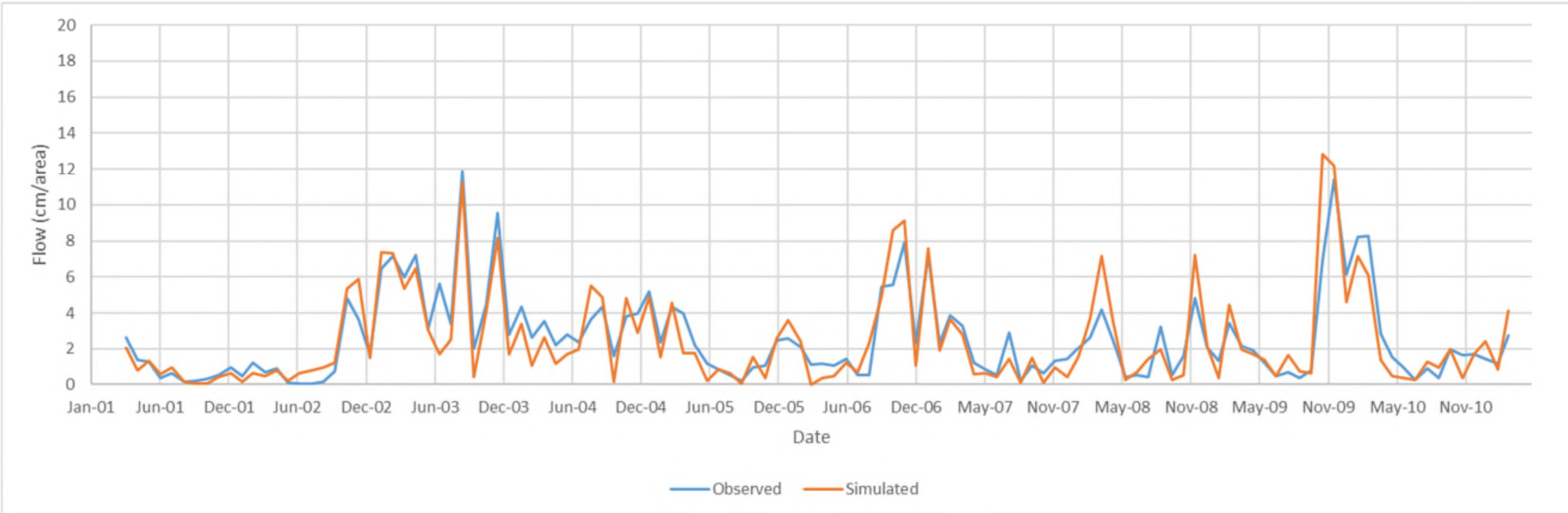

Figure 4-4. Validation data set of simulated stream flow compared to observed flow (USGS#02036500).

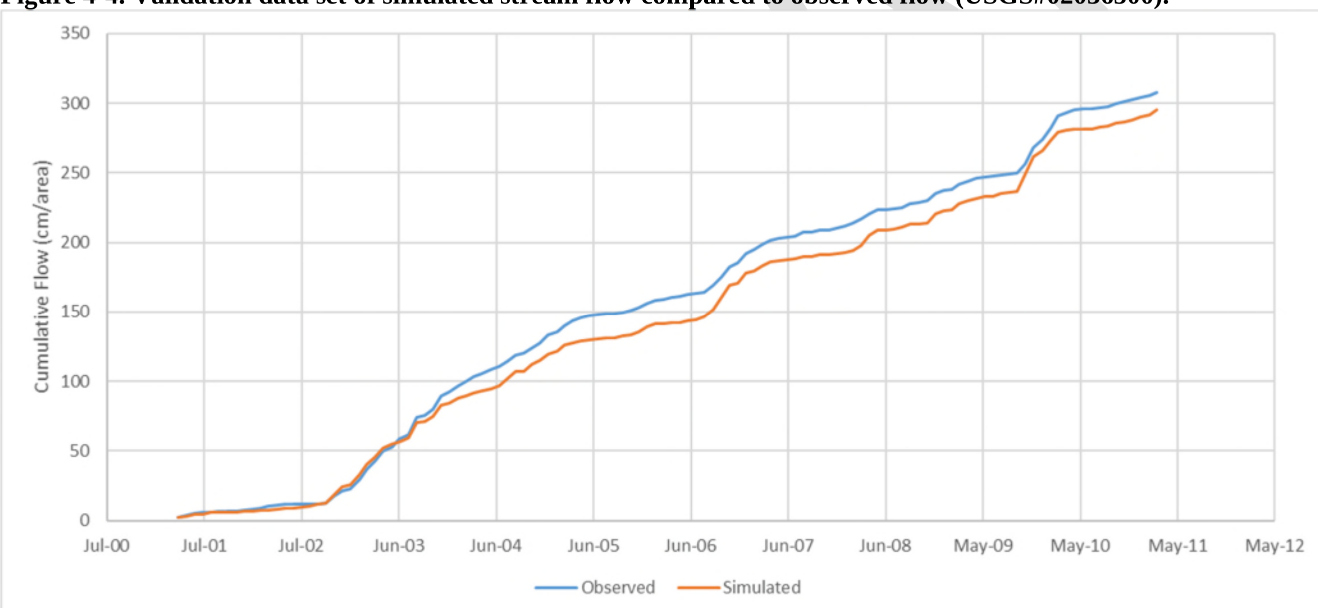

Figure 4-5. Validation data set simulated cumulative flow from model compared to observed (USGS#02036500).

4.7. Existing Conditions

Existing sediment and phosphorus loads from the impaired watersheds were simulated in GWLF as described above. **Table 4-12** through **Table 4-17** summarize the resulting loads for sediment and phosphorus, where appropriate. While the model is run using weather data from a several year period to capture the range of seasonal and annual variation, the land cover and sources within the model do not vary over time as the model runs. Instead, the land cover and pollutant sources simulate a snapshot in time representing available data and active permits. In this model, the land cover is from 2016, the BMPs reflect conditions in May 2020, and permits included are reflective of conditions in July 2020. These dates reflect the collected water quality monitoring data used to determine the necessity of developing this TMDL and to gauge the existing conditions in the model results. The monitoring window for sediment and phosphorus data analyzed for this study ran through June 2020.

Any apparent differences in calculated values are due to rounding. Model results were rounded to 4 significant figures, and calculated totals of those results were rounded to 3 significant figures.

Table 4-12. Existing sediment loads in the Bailey Creek watershed, accounting for known BMPs (not including MOS or FG detailed in Section 6.0). Phosphorus is not a stressor in Bailey Creek.

Bailey Creek Watershed		
Land Cover Category	***TSS (lb/yr)***	***Percentage***
Cropland	26,620	1.3
Hay	6,796	0.3
Pasture	6,592	0.3
Forest	52,790	2.7
Trees	65,790	3.3
Shrub	15,240	0.8
Harvested/Disturbed	38,880	2.0
Water	0	0.0
Wetland	56,730	2.9
Barren	216,700	10.9
Turfgrass	78,630	4.0
Developed, pervious	10,940	0.6
Developed, impervious	219,200	11.1
Streambank	410,600	20.7
Permitted	779,500	39.1
Total	*1,990,000*	*100*

Table 4-13. Existing sediment loads in the Nuttree Branch watershed, accounting for known BMPs (not including MOS or FG detailed in Section 4.4.). Phosphorus is not a stressor in Nuttree Branch

Nuttree Branch Watershed		
Land Cover Category	***TSS (lb/yr)***	***Percentage***
Cropland	0	0.0
Hay	0	0.0
Pasture	0	0.0
Forest	16,410	2.06
Trees	32,270	4.05
Shrub	10,830	1.36
Harvested/Disturbed	0	0.00
Water	0	0.00
Wetland	4,520	0.57
Barren	0	0.00
Turfgrass	44,640	5.60
Developed, pervious	3547	0.45
Developed, impervious	164,700	20.66
Streambank	68,130	8.55
Permitted	452,000	56.71
Total	*797,000*	*100*

Table 4-14. Existing sediment and phosphorus loads in the Oldtown Creek watershed, accounting for known BMPs (not including MOS or FG detailed in Section 4.4.).

Oldtown Creek Watershed				
Land Cover Category	***TSS (lb/yr)***	***Percentage***	***TP (lb/yr)***	***Percentage***
Cropland	159,200	10.5	102	3.9
Hay	6,105	0.4	85	3.2
Pasture	1,690	0.1	3	0.1
Forest	37,250	2.5	18	0.7
Trees	19,720	1.3	13	0.5
Shrub	5,024	0.3	1	0.0
Harvested/Disturbed	24,670	1.6	7	0.3
Water	0	0.0	0	0.0
Wetland	37,550	2.5	4	0.2
Barren	11,290	0.7	1	0.0
Turfgrass	31,170	2.1	239	9.1
Developed, pervious	3,218	0.2	5	0.2
Developed, impervious	179,100	11.9	394	15.1
Streambank	337,800	22.4	118	4.5
Groundwater	-	-	151	5.8
Septic	-	-	1	0.0
Permitted	657,400	43.5	1,465	56.1
Total	*1,510,000*	*100*	*2,610*	*100*

Table 4-15. Existing sediment loads in the Proctors Creek watershed, accounting for known BMPs (not including MOS or FG detailed in Section 4.4.). Phosphorus is not a stressor in Proctors Creek.

Proctors Creek Watershed		
Land Cover Category	***TSS (lb/yr)***	***Percentage***
Cropland	8,824	0.3
Hay	2,111	0.1
Pasture	3,043	0.1
Forest	36,460	1.2
Trees	45,160	1.4
Shrub	8,735	0.3
Harvested/Disturbed	0	0.0
Water	0	0.0
Wetland	68,880	2.2
Barren	199,600	6.3
Turfgrass	58,680	1.9
Developed, pervious	4,151	0.1
Developed, impervious	361,100	11.4
Streambank	955,900	30.2
Permitted	1,413,000	44.6
Total	*3,170,000*	*100*

Table 4-16. Existing sediment and phosphorus loads in the Rohoic Creek watershed, accounting for known BMPs (not including MOS or FG detailed in Section 4.4.).

Rohoic Creek Watershed				
Land Cover Category	***TSS (lb/yr)***	***Percentage***	***TP (lb/yr)***	***Percentage***
Cropland	52,140	4.1	31	1.4
Hay	16,410	1.3	113	5.0
Pasture	4,153	0.3	4	0.2
Forest	22,270	1.7	10	0.4
Trees	31,910	2.5	14	0.6
Shrub	9,145	0.7	2	0.1
Harvested/Disturbed	4,129	0.3	1	0.1
Water	0	0.0	0	0.0
Wetland	21,340	1.7	3	0.1
Barren	0	0.0	0	0.0
Turfgrass	68,250	5.3	291	12.9
Developed, pervious	9,356	0.7	10	0.4
Developed, impervious	198,800	15.5	437	19.4
Streambank	247,200	19.3	87	3.8
Groundwater	-	-	122	5.4
Septic	-	-	1	0.0
Permitted	594,100	46.4	1,128	50.1
Total	*1,280,000*	*100*	*2,250*	*100*

Table 4-17. Existing sediment and phosphorus loads in the Swift Creek watershed (including Nuttree Branch), accounting for known BMPs (not including MOS or FG detailed in Section 4.4.).

Swift Creek Watershed				
Land Cover Category	***TSS (lb/yr)***	***Percentage***	***TP (lb/yr)***	***Percentage***
Cropland	119,500	0.6	71	0.4
Hay	26,210	0.1	363	1.9
Pasture	144,700	0.8	191	1.0
Forest	322,110	1.7	143	0.8
Trees	174,570	0.9	115	0.6
Shrub	30,690	0.2	3	0.0
Harvested/Disturbed	70,200	0.4	23	0.1
Water	0	0.0	0	0.0
Wetland	138,820	0.7	8	0.0
Barren	668,000	3.5	44	0.2
Turfgrass	200,140	1.0	1,267	6.7
Developed, pervious	24,507	0.1	35	0.2
Developed, impervious	1,681,700	8.8	4,237	22.3
Streambank	11,038,130	57.5	4,383	23.1
Groundwater	-	-	1,588	8.4
Septic	-	-	17	0.1
Permitted	4,553,000	23.7	6,535	34.4
Total	*19,200,000*	*100*	*19,000*	*100*

5.0 SETTING TARGET SEDIMENT LOADS

TMDL development requires an endpoint or water quality goal to target for the impaired watershed(s). Many pollutants have numeric water quality criteria set in regulatory documentation, and it is assumed that compliance with these numeric criteria will lead the waterbody to achieve support of all designated uses. However, sediment and phosphorus do not have numeric criteria established, as the acceptable level is expected to vary from stream to stream based on a range of contributing factors. Therefore, an alternative method must be used to determine the water quality targets for sediment and phosphorus TMDLs.

The method used to set TMDL endpoint loads for the James River tributaries watersheds is called the "all-forest load multiplier" (AllForX) approach, which has been used in developing many sediment and nutrient TMDLs in Virginia since 2014. AllForX is the ratio of the simulated pollutant load under existing conditions to the pollutant load from an all-forest simulated condition for the same watershed. In other words, AllForX is an indication of how much higher current sediment or nutrient loads are above an undeveloped condition. These ratios were calculated for a total of 15 watersheds (both impaired and unimpaired) of similar size and within the same ecoregion as the TMDL watersheds (**Appendix C**). A regression was then developed between the Virginia Stream Condition Index (VSCI) scores at monitoring stations and the corresponding AllForX value calculated for the watershed draining to each station. This regression was used to quantify the AllForX value that corresponds to the benthic health threshold (VSCI = 60). **Figure 5-1** and **Figure 5-2** show the regressions developed for the James River Tributaries study for sediment and phosphorus, respectively. The allowable pollutant TMDL load was then calculated by applying the AllForX threshold where VSCI = 60 (AllForX TSS = 5.85, AllForX TP = 3.36) to the all-forest simulated pollutant load of the TMDL study watershed, as summarized in (**Table 5-1** and **Table 5-2**).

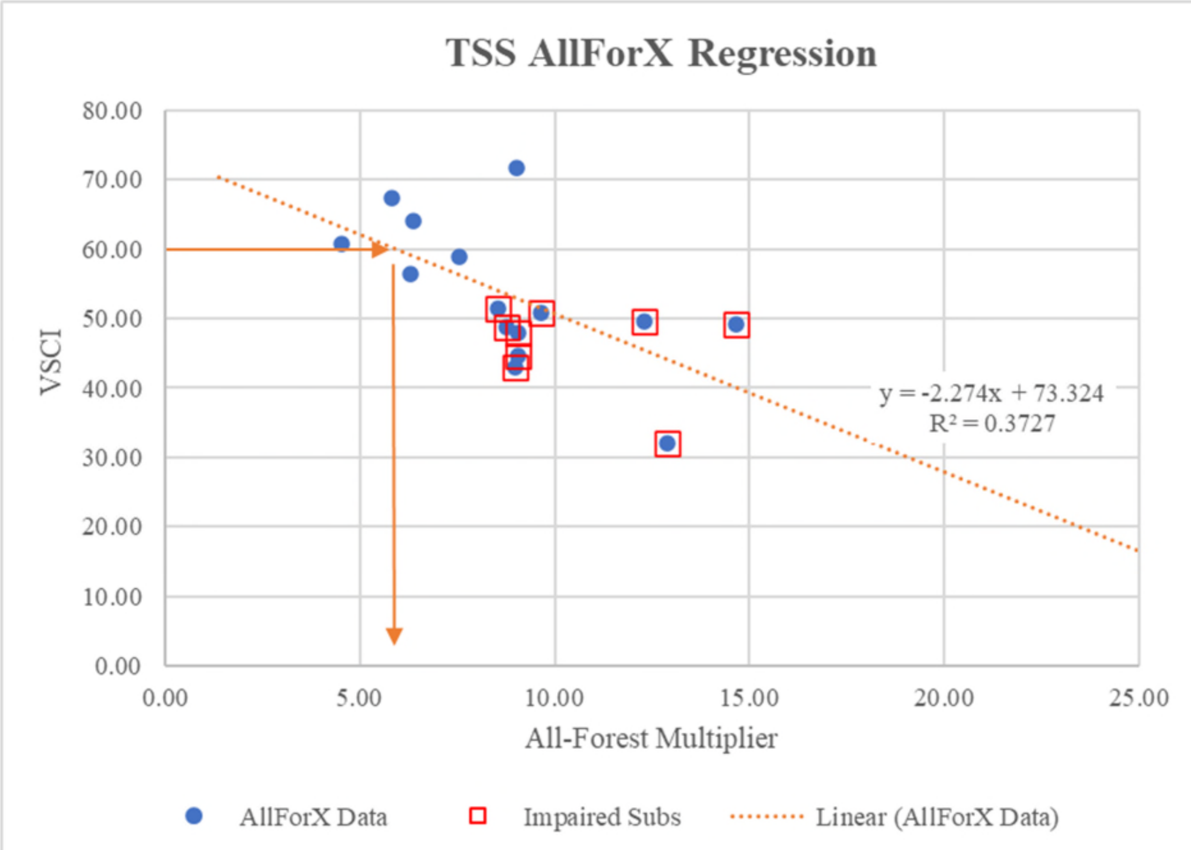

Figure 5-1. Regression between stream condition index and all-forest multiplier for sediment in the James River tributaries TMDL using VSCI scores, resulting in an AllForX target value of 5.85.

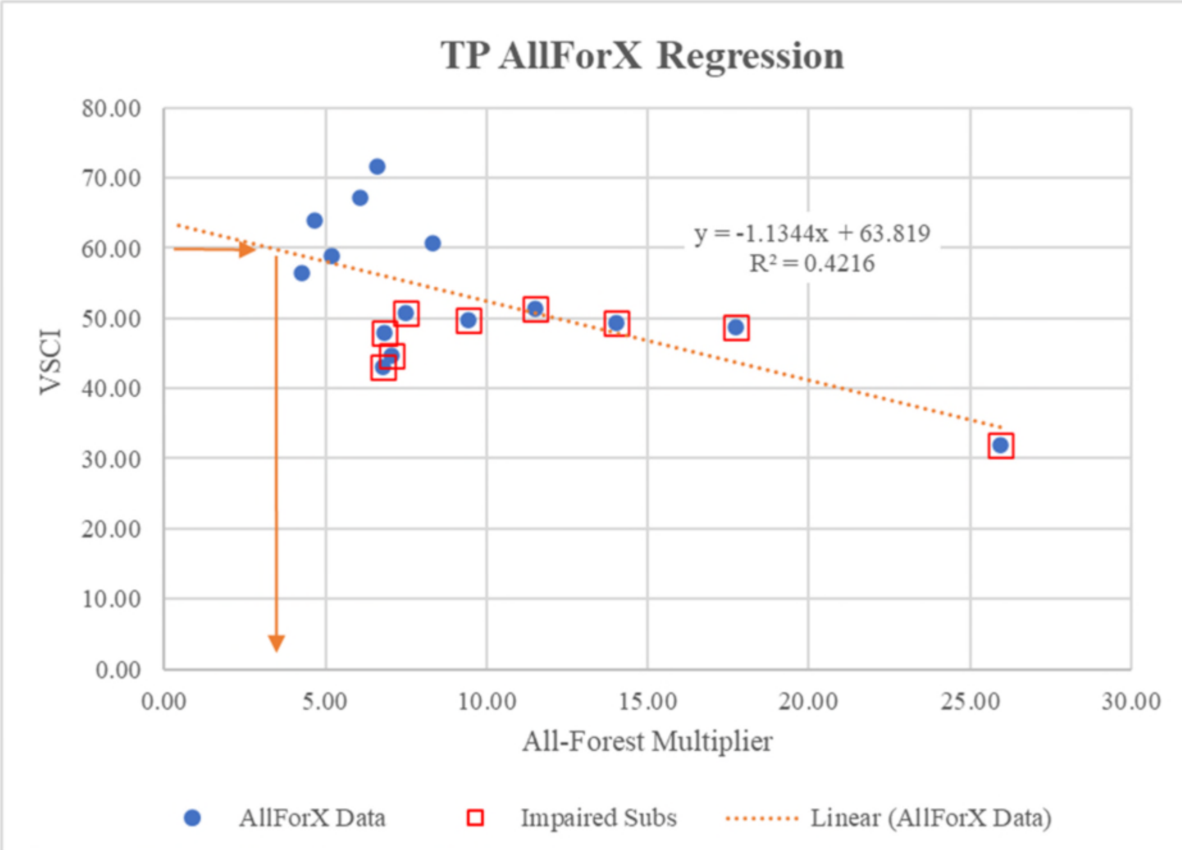

Figure 5-2 Regression between stream condition index and all-forest multiplier for phosphorus in the James River tributaries TMDL using VSCI scores, resulting in an AllForX target value of 3.36.

Table 5-1. Target sediment loading rates as determined by the AllForX regression multiplier of 5.85.

Impaired Stream	**TSS AllForest** (lb/yr)	**TSS Target** (lb/yr)
Bailey Creek	204,200	1,200,000
Nuttree Branch	90,930	533,000
Oldtown Creek	106,700	625,000
Proctors Creek	174,200	1,020,000
Rohoic Creek	110,700	649,000
Swift Creek	1,875,000	11,000,000

Table 5-2. Target phosphorus loading rates as determined by the AllForX regression multiplier of 3.36

Impaired Stream	**TP AllForest** (lb/yr)	**TP Target** (lb/yr)
Oldtown Creek	269	904
Rohoic Creek	194	654
Swift Creek	2,594	8,730

6.0 TMDL ALLOCATIONS

Total Maximum Daily Loads (TMDLs) are determined as the maximum allowable load of a pollutant. Part of developing a TMDL is allocating this load among the various sources of the pollutant of concern (POC). Each TMDL is comprised of three components, as summed up in this equation:

$$TMDL = \sum WLA + \sum LA + MOS$$

where ΣWLA is the sum of the wasteload allocations (permitted sources),
ΣLA is the sum of the load allocations (non-point sources), and
MOS is a margin of safety.

The wasteload allocation (WLA) is calculated as the sum of all the permitted sources of the POC within the watershed as if they were discharging at their permitted allowable rate. A description of the permitted sources and their permitted loads are included in **Section 4.3.2**. The margin of safety (MOS) is determined based on the characteristics of the watershed and the model used to develop the TMDL loads (see **Section 6.1**). The overall load allocation (LA) is then calculated by subtracting the total WLA and MOS from the TMDL. Various allocation scenarios are typically developed to show different breakdowns of how this LA can be divided among the various non-point sources of the POC, stakeholder input is used to determine the most favorable allocation scenario for a particular watershed.

To develop the annual existing loads and target loads using the AllForX methodology, a 20-year period was simulated (2001 through 2021) with an additional buffer period of nine months at the beginning of the run to serve as a 'warm-up' period for the model to equilibrate and minimize the impact of uncertain initial conditions. Using this extended modeling period allows the results to account for both annual and seasonal variations in hydrology and sediment/phosphorus loading.

6.1. Margin of Safety

To account for uncertainties inherent in model outputs, a margin of safety (MOS) is incorporated into the TMDL development process. The MOS can be implicit, explicit, or a combination of the two. An implicit MOS involves incorporating conservative assumptions into the modeling process to ensure that the final TMDL is protective of water quality considering the unavoidable uncertainty in the modeling process. A MOS can also be incorporated explicitly into the TMDL development by setting aside a portion of the TMDL.

This TMDL includes both implicit and explicit MOSs. An example of implicit MOS assumptions incorporated into this TMDL are the inclusion of permitted loads at their maximum permitted rates, even when data shows that they are consistently discharging well below that threshold. An explicit MOS of 10% is also included in the sediment and phosphorus TMDLs.

6.2. Future Growth

An allocation of 2% of the total load is specifically set aside for future growth within this TMDL. This leaves flexibility in the plan for future permitted loads to be added within the watersheds, as the development of a TMDL looks at a snapshot in time of a dynamic system within the watershed and is not meant to prevent future economic growth.

6.3. TMDL Calculations

Sediment was determined in the stressor analysis (**Appendix D**) as a primary cause of the benthic impairments in each of the impaired watersheds. Phosphorus was also determined to be a primary cause of the impairment in Oldtown Creek, Rohoic Creek, and Swift Creek. TMDLs were developed for sediment in each impaired watershed, and an additional TMDL for phosphorus was developed for Oldtown, Rohoic, and Swift.

6.3.1. Annual Average Loads

Total loads to downstream subwatersheds were summed from the loads of each contributing upstream subwatershed. The final sediment and phosphorus average annual loads allocated in the TMDL are presented in **Table 6-1** through **Table 6-6** and **Table 6-7** through **Table 6-9**, respectively. GWLF output data, being in monthly increments, is most logically presented as annual aggregates. Any apparent differences in calculated values are due to rounding. Model results were rounded to four significant figures, and calculated totals of those results were rounded to three significant figures.

Table 6-1. Annual average sediment TMDL components for Bailey Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TSS)	Allocated Nonpoint Sources (LA) (lb/yr TSS)	Margin of Safety (MOS) (lb/yr TSS)	Total Maximum Daily Load (TMDL) (lb/yr TSS)	Existing Load (lb/yr TSS)	Overall Reduction (%)
Bailey Creek (VAP-G03R_BLY02A08, VAP-G03R_BLY01A98)	**424,000**	**656,400**	**119,600**	**1,200,000**	2,130,000	43.7%
VA0059161	*5,245*					
Concrete Facility Permits	*1,945*					
ISW Permits	*43,060*					
MS4 Permits	*316,500*					
Construction Permits	*33,500*					
Future Growth (2% of TMDL)	*23,930*					

Table 6-2. Annual average sediment TMDL components for Nuttree Branch.

Impairment	Allocated Point Sources (WLA) (lb/yr TSS)	Allocated Nonpoint Sources (LA) (lb/yr TSS)	Margin of Safety (MOS) (lb/yr TSS)	Total Maximum Daily Load (TMDL) (lb/yr TSS)	Existing Load (lb/yr TSS)	Overall Reduction (%)
Nuttree Branch (VAP-J17R_NUT01A06)	**303,000**	**177,000**	**53,300**	**533,000**	861,000	38.1%
NMMM Permits	*45,700*					
Concrete Facility Permits	*326*					
ISW Permits	*8,888*					
MS4 Permits	*107,300*					
Construction Permits	*129,600*					
Future Growth (2% of TMDL)	*10,700*					

Table 6-3. Annual average sediment TMDL components for Oldtown Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TSS)	Allocated Nonpoint Sources (LA) (lb/yr TSS)	Margin of Safety (MOS) (lb/yr TSS)	Total Maximum Daily Load (TMDL) (lb/yr TSS)	Existing Load (lb/yr TSS)	Overall Reduction (%)
Oldtown Creek (VAP-J15R_OTC01A00 VAP-J15R_OTC01B08)	**253,000**	**308,500**	**62,520**	**624,000**	1,590,000	60.8%
MS4 Permits	*159,700*					
Construction Permits	*80,810*					
Future Growth (2% of TMDL)	*12,500*					

Table 6-4. Annual average sediment TMDL components for Proctors Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TSS)	Allocated Nonpoint Sources (LA) (lb/yr TSS)	Margin of Safety (MOS) (lb/yr TSS)	Total Maximum Daily Load (TMDL) (lb/yr TSS)	Existing Load (lb/yr TSS)	Overall Reduction (%)
Proctors Creek (VAP-G01R_PCT01A06)	**573,000**	**345,000**	**102,100**	**1,020,000**	3,290,000	69.0%
Concrete Facility Permits	*1,188*					
ISW Permits	*64,760*					
Vehicle Wash Permits	*55*					
MS4 Permits	*112,900*					
Construction Permits	*373,600*					
Future Growth (2% of TMDL)	*20,420*					

Table 6-5. Annual average sediment TMDL components for Rohoic Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TSS)	Allocated Nonpoint Sources (LA) (lb/yr TSS)	Margin of Safety (MOS) (lb/yr TSS)	Total Maximum Daily Load (TMDL) (lb/yr TSS)	Existing Load (lb/yr TSS)	Overall Reduction (%)
Rohoic Creek (VAP-J15R_RHC01A06)	**377,000**	**206,000**	**64,870**	**648,000**	1,360,000	52.4%
NMMM Permits	*127,900*					
Concrete Facility Permits	*4,586*					
ISW Permits	*57,800*					
MS4 Permits	*43,510*					
Construction Permits	*130,500*					
Future Growth (2% of TMDL)	*12,970*					

Table 6-6. Annual average sediment TMDL components for Swift Creek (Nuttree Branch represented within the LA).

Impairment	Allocated Permitted Point Sources (WLA) (lb/yr TSS)	Allocated Nonpoint Sources (LA) (lb/yr TSS)	Margin of Safety (MOS) (lb/yr TSS)	Total Maximum Daily Load (TMDL) (lb/yr TSS)	Existing Load (lb/yr TSS)	Overall Reduction (%)
Swift Creek (VAP-J17R_SFT01B98, VAP-J17R_SFT02A00)	**2,870,000**	**7,030,000**	**1,099,000**	**11,000,000**	20,100,000	45.3%
VA0006254	*91,380*					
VA0023426	*8,910*					
NMMM Permits	*137,100*					
ISW Permits	*101,700*					
Domestic Sewage Permits	*366*					
MS4 Permits	*993,200*					
Construction Permits	*1,314,000*					
Future Growth (2% of TMDL)	*219,800*					

Table 6-7. Annual average phosphorus TMDL components for Oldtown Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TP)	Allocated Nonpoint Sources (LA) (lb/yr TP)	Margin of Safety (MOS) (lb/yr TP)	Total Maximum Daily Load (TMDL) (lb/yr TP)	Existing Load (lb/yr TP)	Overall Reduction (%)
Oldtown Creek (VAP-J15R_OTC01A00, VAP-J15R_OTC01B08)	**404**	**407**	**91**	**902**	2,720	66.8%
MS4 Permits	*327.7*					
Construction Permits	*58.2*					
Future Growth (2% of TMDL)	*18.1*					

Table 6-8. Annual average phosphorus TMDL components for Rohoic Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TP)	Allocated Nonpoint Sources (LA) (lb/yr TP)	Margin of Safety (MOS) (lb/yr TP)	Total Maximum Daily Load (TMDL) (lb/yr TP)	Existing Load (lb/yr TP)	Overall Reduction (%)
Rohoic Creek (VAP-J15R_RHC01A06)	**426**	**163**	**65**	**654**	2,330	71.0%
NMMM Permits	*85.3*					
Concrete Facility Permits	*31.0*					
ISW Permits	*197.0*					
MS4 Permits	*6.3*					
Construction Permits	*94.0*					
Future Growth (2% of TMDL)	*13.1*					

Table 6-9. Annual average phosphorus TMDL components for Swift Creek.

Impairment	Allocated Point Sources (WLA) (lb/yr TP)	Allocated Nonpoint Sources (LA) (lb/yr TP)	Margin of Safety (MOS) (lb/yr TP)	Total Maximum Daily Load (TMDL) (lb/yr TP)	Existing Load (lb/yr TP)	Overall Reduction (%)
Swift Creek (VAP-J17R_SFT01B98, VAP-J17R_SFT02A00)	**3,150**	**4,700**	**873**	**8,720**	20,200	56.8%
VA0006254	*9.6*					
VA0023426	*46.0*					
NMMM Permits	*121.8*					
ISW Permits	*377.1*					
Domestic Sewage Permits	*17.2*					
MS4 Permits	*1,354*					
Construction Permits	*1,040*					
Future Growth (2% of TMDL)	*174.6*					

6.3.2. Maximum Daily Loads

In 1991, the USEPA released a support document that included guidance for developing maximum daily loads (MDLs) for TMDLs (USEPA, 1991). A methodology detailed therein was used to determine the MDLs for the watersheds. The long-term average (LTA) daily loads, derived by dividing the average annual loads in **Table 6-1** through **Table 6-9** by 365.24, are converted to MDLs using the following equation:

$$MDL = LTA * \exp\left(Z_p \sigma_y - 0.5\sigma_y^2\right)$$

where Z_p = pth percentage point of the normal standard deviation, and
σ_y = sqrt(ln(CV^2+1)), with CV = coefficient of variation of the data.

The variable Z_p was set to 1.645 for this TMDL development, representing the 95th percentile. The CV values and final calculated multipliers to convert LTA to MDL values are summarized in **Table 6-10**.

Table 6-10. "LTA to MDL multiplier" components for TSS and TP TMDLs.

Pollutant	Watershed	CV of Average Annual Loads	"LTA to MDL Multiplier"
Sediment	Bailey Creek	0.23	1.42
	Nuttree Branch	0.26	1.47
	Oldtown Creek	0.23	1.42
	Proctors Creek	0.24	1.43
	Rohoic Creek	0.23	1.42
	Swift Creek	0.23	1.42
Phosphorus	Oldtown Creek	0.29	1.54
	Rohoic Creek	0.31	1.57
	Swift Creek	0.28	1.52

The daily WLA was estimated as the annual WLA divided by 365.24. The daily MOS was estimated as 10% of the MDL. Finally, the daily LA was estimated as the MDL minus the daily MOS minus the daily WLA. These results are shown in **Table 6-11** through **Table 6-16** and **Table 6-17** through **Table 6-19** for sediment and phosphorus, respectively.

Table 6-11. Maximum 'daily' sediment loads and components for Bailey Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TSS)	Allocated Nonpoint Sources (LA) (lb/day TSS)	Margin of Safety (MOS) (lb/day TSS)	Maximum Daily Load (MDL) (lb/day TSS)
Bailey Creek (VAP-G03R_BLY02A08, VAP-G03R_BLY01A98)	**1,161**	**3,038**	**467**	**4,665**
VA0059161	*14.4*			
Concrete Facility Permits	*5.3*			
ISW Permits	*117.9*			
MS4 Permits	*866.6*			
Construction Permits	*91.7*			
Future Growth (2% of TMDL)	*65.5*			

Table 6-12. Maximum ‘daily’ sediment loads and components for Nuttree Branch.

Impairment	Allocated Point Sources (WLA) (lb/day TSS)	Allocated Nonpoint Sources (LA) (lb/day TSS)	Margin of Safety (MOS) (lb/day TSS)	Maximum Daily Load (MDL) (lb/day TSS)
Nuttree Branch (VAP-J17R_NUT01A06)	**830**	**1,101**	**215**	**2,145**
NMMM Permits	*125.1*			
Concrete Facility Permits	*0.9*			
ISW Permits	*24.3*			
MS4 Permits	*293.8*			
Construction Permits	*355*			
Future Growth (2% of TMDL)	*29*			

Table 6-13. Maximum ‘daily’ sediment loads and components for Oldtown Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TSS)	Allocated Nonpoint Sources (LA) (lb/day TSS)	Margin of Safety (MOS) (lb/day TSS)	Maximum Daily Load (MDL) (lb/day TSS)
Oldtown Creek (VAP-J15R_OTC01A00 VAP-J15R_OTC01B08)	**693**	**1,491**	**243**	**2,426**
MS4 Permits	*437.2*			
Construction Permits	*221.3*			
Future Growth (2% of TMDL)	*34.2*			

Table 6-14. Maximum ‘daily’ sediment loads and components for Proctors Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TSS)	Allocated Nonpoint Sources (LA) (lb/day TSS)	Margin of Safety (MOS) (lb/day TSS)	Maximum Daily Load (MDL) (lb/day TSS)
Proctors Creek (VAP-G01R_PCT01A06)	**1,569**	**2,025**	**399**	**3,994**
Concrete Facility Permits	*3.3*			
ISW Permits	*177.3*			
Vehicle Wash Permits	*0.2*			
MS4 Permits	*309.1*			
Construction Permits	*1,023*			
Future Growth (2% of TMDL)	*56*			

Table 6-15. Maximum 'daily' sediment loads and components for Rohoic Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TSS)	Allocated Nonpoint Sources (LA) (lb/day TSS)	Margin of Safety (MOS) (lb/day TSS)	Maximum Daily Load (MDL) (lb/day TSS)
Rohoic Creek (VAP-J15R_RHC01A06)	**1,032**	**1,235**	**252**	**2,519**
NMMM Permits	*350.2*			
Concrete Facility Permits	*12.6*			
ISW Permits	*158.3*			
MS4 Permits	*119.1*			
Construction Permits	*357*			
Future Growth (2% of TMDL)	*36*			

Table 6-16. Maximum 'daily' sediment loads and components for Swift Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TSS)	Allocated Nonpoint Sources (LA) (lb/day TSS)	Margin of Safety (MOS) (lb/day TSS)	Maximum Daily Load (MDL) (lb/day TSS)
Swift Creek (VAP-J17R_SFT01B98, VAP-J17R_SFT02A00)	**7,858**	**30,632**	**4,277**	**42,766**
VA0006254	*250.2*			
VA0023426	*24.4*			
NMMM Permits	*375.4*			
ISW Permits	*278.4*			
Domestic Sewage Permits	*1.0*			
MS4 Permits	*2,719.3*			
Construction Permits	*3,598*			
Future Growth (2% of TMDL)	*602*			

Table 6-17. Maximum 'daily' phosphorus loads and components for Oldtown Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TP)	Allocated Nonpoint Sources (LA) (lb/day TP)	Margin of Safety (MOS) (lb/day TP)	Maximum Daily Load (MDL) (lb/day TP)
Oldtown Creek (VAP-J15R_OTC01A00 VAP-J15R_OTC01B08)	**1.1**	**2.3**	**0.4**	**3.8**
MS4 Permits	*0.9*			
Construction Permits	*0.2*			
Future Growth (2% of TMDL)	*0.05*			

Table 6-18. Maximum 'daily' phosphorus loads and components for Rohoic Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TP)	Allocated Nonpoint Sources (LA) (lb/day TP)	Margin of Safety (MOS) (lb/day TP)	Maximum Daily Load (MDL) (lb/day TP)
Rohoic Creek (VAP-J15R_RHC01A06)	**1.2**	**1.4**	**0.3**	**2.8**
NMMM Permits	*0.2*			
Concrete Facility Permits	*0.1*			
ISW Permits	*0.5*			
MS4 Permits	*0.0*			
Construction Permits	*0.3*			
Future Growth (2% of TMDL)	*0.04*			

Table 6-19. Maximum 'daily' phosphorus loads and components for Swift Creek.

Impairment	Allocated Point Sources (WLA) (lb/day TP)	Allocated Nonpoint Sources (LA) (lb/day TP)	Margin of Safety (MOS) (lb/day TP)	Maximum Daily Load (MDL) (lb/day TP)
Swift Creek (VAP-J17R_SFT01B98, VAP-J17R_SFT02A00)	**8.6**	**24.0**	**3.6**	**36.3**
VA0006254	*0.03*			
VA0023426	*0.1*			
NMMM Permits	*0.3*			
ISW Permits	*1.0*			
Domestic Sewage Permits	*0.05*			
MS4 Permits	*3.7*			
Construction Permits	*2.8*			
Future Growth (2% of TMDL)	*0.5*			

6.4. Allocation Scenarios

Multiple allocation scenarios were run to determine possible options for reducing the sediment and phosphorus loads to the recommended TMDL loads. Feedback from the TAC members guided the selection of the preferred allocation scenarios for each TMDL watershed. TAC members indicated that an even percentage-based reduction across all sediment and phosphorus sources was preferred for all study watersheds. The various sediment allocation scenarios are presented in **Table 6-20** through **Table 6-25,** and the various phosphorus allocation scenarios are presented in **Table 6-26** through **Table 6-28.** The selected allocation scenario for each watershed is Scenario 1.

Due to the level of reductions needed in the Rohoic Creek watershed, discussions between VADEQ and permittees resulted in the decision to reduce the allocated TSS and TP loading rates calculated for ISW permits in the Rohoic Creek watershed by 50%. Based on collected data, the majority of the ISW permits in the Rohoic Creek watershed are already discharging below the typical permitted rate.

Any apparent differences in calculated values are due to rounding. Model results were rounded to four significant figures, and calculated totals of those results were rounded to three significant figures.

Table 6-20. Allocation scenarios for Bailey Creek sediment loads.

Bailey Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**
Cropland	26,620	54.5	12,110	40.8	15,760	77.1	6,096
Hay	6,796	54.5	3,092	40.8	4,024	77.1	1,556
Pasture	6,592	54.5	2,999	40.8	3,902	77.1	1,510
Forest	52,790	-	52,790	-	52,790	-	52,790
Trees	65,790	-	65,790	-	65,790	-	65,790
Shrub	15,240	-	15,240	-	15,240	-	15,240
Harvested	38,880	54.5	17,690	40.8	23,020	77.1	8,904
Wetland	56,730	-	56,730	-	56,730	-	56,730
Barren	216,700	54.5	98,610	60.0	86,690	45.5	118,100
Turfgrass	78,630	54.5	35,780	60.0	31,450	45.5	42,850
Developed Pervious	10,940	54.5	4,975	60.0	4,374	45.5	5,960
Developed Impervious	219,200	54.5	99,720	60.0	87,660	45.5	119,400
Streambank Erosion	410,600	54.5	186,800	40.8	243,100	77.1	94,020
VA0059161	5,245	-	5,245	-	5,245	-	5,245
Concrete Facility Permits	1,945	-	1,945	-	1,945	-	1,945
ISW Permits	43,060	-	43,060	-	43,060	-	43,060
MS4	695,700	54.5	316,500	60.0	278,300	45.5	379,100
Construction Permits	33,500	-	33,500	-	33,500	-	33,500
Future Growth (2%)	23,930	-	23,930	-	23,930	-	23,930
MOS (10%)	119,600	-	119,600	-	119,600	-	119,600
TOTAL	**2,130,000**	**43.7**	**1,200,000**	**43.7**	**1,200,000**	**43.7**	**1,200,000**

Table 6-21. Allocation scenarios for Nuttree Branch sediment loads.

Nuttree Branch Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**
Cropland	-	-	-	-	-	-	-
Hay	-	-	-	-	-	-	-
Pasture	-	-	-	-	-	-	-
Forest	16,410	-	16,410	-	16,410	-	16,410
Trees	32,270	-	32,270	-	32,270	-	32,270
Shrub	10,830	-	10,830	-	10,830	-	10,830
Harvested	-	-	-	-	-	-	-
Wetland	4,520	-	4,520	-	4,520	-	4,520
Barren	-	-	-	68.4	-	62.7	-
Turfgrass	44,640	59.9	17,900	68.4	14,110	62.7	16,650
Developed Pervious	3,547	59.9	1,422	68.4	1,121	62.7	1,323
Developed Impervious	164,700	59.9	66,040	68.4	52,040	62.7	61,430
Streambank Erosion	68,130	59.9	27,320	-	68,130	40.0	40,880
NMMM Permits	45,690	-	45,690	-	45,690	-	45,690
Concrete Facility Permits	326	-	326	-	326	-	326
ISW Permits	8,888	-	8,888	-	8,888	-	8,888
MS4	267,500	59.9	107,300	68.4	84,550	62.7	99,800
Construction Permits	129,600	-	129,600	-	129,600	-	129,600
Future Growth (2%)	10,660	-	10,660	-	10,660	-	10,660
MOS (10%)	53,280	-	53,280	-	53,280	-	53,280
TOTAL	**861,000**	**38.2**	**532,000**	**38.2**	**532,000**	**38.1**	**533,000**

Table 6-22. Allocation scenarios for Oldtown Creek sediment loads.

Oldtown Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**
Cropland	159,200	72.3	44,090	40.0	95,510	81.5	29,450
Hay	6,105	72.3	1,691	40.0	3,663	81.5	1,129
Pasture	1,690	72.3	468	40.0	1,014	81.5	313
Forest	37,250	-	37,250	-	37,250	-	37,250
Trees	19,720	-	19,720	-	19,720	-	19,720
Shrub	5,024	-	5,024	-	5,024	-	5,024
Harvested	24,670	72.3	6,834	40.0	14,800	81.5	4,564
Wetland	37,550	-	37,550	-	37,550	-	37,550
Barren	11,290	72.3	3,127	77.7	2,517	81.5	2,088
Turfgrass	31,170	72.3	8,635	77.7	6,952	81.5	5,767
Developed Pervious	3,218	72.3	891	77.7	718	81.5	595
Developed Impervious	179,100	72.3	49,620	77.7	39,940	81.5	33,140
Streambank Erosion	337,800	72.3	93,580	77.7	75,340	45.0	185,800
MS4	576,600	72.3	159,700	77.7	128,600	81.5	106,700
Construction Permits	80,810	-	80,810	-	80,810	-	80,810
Future Growth (2%)	12,500	-	12,500	-	12,500	-	12,500
MOS (10%)	62,520	-	62,520	-	62,520	-	62,520
TOTAL	**1,590,000**	**60.8**	**624,000**	**60.8**	**624,000**	**60.7**	**625,000**

Table 6-23. Allocation scenarios for Proctors Creek sediment loads.

Proctors Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**
Cropland	8,824	88.4	1,024	-	8,824	50.0	4,412
Hay	2,111	88.4	245	-	2,111	50.0	1,055
Pasture	3,043	88.4	353	-	3,043	50.0	1,521
Forest	36,460	-	36,460	-	36,460	-	36,460
Trees	45,160	-	45,160	-	45,160	-	45,160
Shrub	8,735	-	8,735	-	8,735	-	8,735
Harvested	-	88.4	-	-	-	50.0	-
Wetland	68,880	-	68,880	-	68,880	-	68,880
Barren	199,600	88.4	23,160	88.9	22,160	88.6	22,760
Turfgrass	58,680	88.4	6,807	88.9	6,514	88.6	6,690
Developed Pervious	4,151	88.4	482	88.9	461	88.6	473
Developed Impervious	361,100	88.4	41,880	88.9	40,080	88.6	41,160
Streambank Erosion	955,900	88.4	110,900	88.9	106,100	88.6	109,000
Concrete Facility Permits	1,188	-	1,188	-	1,188	-	1,188
Vehicle Wash Permits	55	-	55	-	55	-	55
ISW Permits	64,760	-	64,760	-	64,760	-	64,760
MS4	973,100	88.4	112,900	88.9	108,000	88.6	110,900
Construction Permits	373,600	-	373,600	-	373,600	-	373,600
Future Growth (2%)	20,420	-	20,420	-	20,420	-	20,420
MOS (10%)	102,100	-	102,100	-	102,100	-	102,100
TOTAL	**3,290,000**	**69.0**	**1,020,000**	**69.0**	**1,020,000**	**69.0**	**1,020,000**

Table 6-24. Allocation scenarios for Rohoic Creek sediment loads.

Rohoic Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**
Cropland	52,140	79.8	10,530	77.3	11,840	80.0	10,430
Hay	16,410	79.8	3,314	77.3	3,724	80.0	3,281
Pasture	4,153	79.8	839	77.3	943	80.0	831
Forest	22,270	-	22,270	-	22,270	-	22,270
Trees	31,910	-	31,910	-	31,910	-	31,910
Shrub	9,145	-	9,145	-	9,145	-	9,145
Harvested	4,129	79.8	834	77.3	937	80.0	826
Wetland	21,340	-	21,340	-	21,340	-	21,340
Barren	-	79.8	-	80.0	-	79.6	-
Turfgrass	68,250	79.8	13,790	80.0	13,650	79.6	13,920
Developed Pervious	9,356	79.8	1,890	80.0	1,871	79.6	1,909
Developed Impervious	198,800	79.8	40,160	80.0	39,760	79.6	40,560
Streambank Erosion	247,200	79.8	49,930	80.0	49,430	80.0	49,430
NMMM Permits	127,900	-	127,900	-	127,900	-	127,900
Concrete Facility Permits	4,586	-	4,586	-	4,586	-	4,586
ISW Permits	115,600	50.0	57,800	50.0	57,800	50.0	57,800
MS4	215,400	79.8	43,510	80.0	43,080	79.6	43,950
Construction Permits	130,500	-	130,500	-	130,500	-	130,500
Future Growth (2%)	12,970	-	12,970	-	12,970	-	12,970
MOS (10%)	64,870	-	64,870	-	64,870	-	64,870
TOTAL	**1,360,000**	**52.4**	**648,000**	**52.3**	**649,000**	**52.4**	**648,000**

Table 6-25. Allocation scenarios for Swift Creek sediment loads.

Swift Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3		Scenario 4	
Source	**Existing TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**	**Reduction (%)**	**Allocation TSS (lb/yr)**
Cropland	119,500	57.0	51,390	39.6	72,180	83.2	20,080	-	119,500
Hay	26,210	57.0	11,270	39.6	15,830	83.2	4,404	-	26,210
Pasture	144,700	57.0	62,210	39.6	87,380	83.2	24,310	-	144,700
Forest	305,700	-	305,700	-	305,700	-	305,700	-	305,700
Trees	142,300	-	142,300	-	142,300	-	142,300	-	142,300
Shrub	19,860	-	19,860	-	19,860	-	19,860	-	19,860
Harvested	70,200	57.0	30,190	39.6	42,400	83.2	11,790	-	70,200
Wetland	134,300	-	134,300	-	134,300	-	134,300	-	134,300
Barren	668,000	57.0	287,200	39.6	403,500	83.2	112,200	58.4	277,900
Turfgrass	155,500	57.0	66,860	39.6	93,910	83.2	26,120	58.4	64,680
Developed Pervious	20,960	57.0	9,015	39.6	12,660	83.2	3,522	58.4	8,721
Developed Impervious	1,517,000	57.0	652,100	39.6	916,000	83.2	254,800	58.4	630,900
Streambank Erosion	10,970,000	57.0	4,717,000	65.0	3,839,000	45.0	6,033,000	58.4	4,563,000
VA0006254	91,380	-	91,380	-	91,380	-	91,380	-	91,380
VA0023426	8,910	-	8,910	-	8,910	-	8,910	-	8,910
NMMM Permits	137,072	-	137,072	-	137,072	-	137,072	-	137,072
Domestic Sewage Permits	366	-	366	-	366	-	366	-	366
ISW Permits	101,700	-	101,700	-	101,700	-	101,700	-	101,700
MS4	2,310,000	57.0	993,200	39.6	1,395,000	83.2	388,000	58.4	960,900
Construction Permits	1,314,000	-	1,314,000	-	1,314,000	-	1,314,000	-	1,314,000
Future Growth (2%)	219,800	-	219,800	-	219,800	-	219,800	-	219,800
Nuttree Branch TMDL Target	533,000	-	533,000	-	533,000	-	533,000	-	533,000
MOS (10%)	1,099,000	-	1,099,000	-	1,099,000	-	1,099,000	-	1,099,000
TOTAL	**20,100,000**	**45.3**	**11,000,000**	**45.3**	**11,000,000**	**45.3**	**11,000,000**	**45.3**	**11,000,000**

Table 6-26. Allocation scenarios for Oldtown Creek phosphorus loads.

Oldtown Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**
Cropland	102.4	76.7	23.9	50.0	51.2	78.7	21.8
Hay	84.8	76.7	19.8	50.0	42.4	78.7	18.1
Pasture	3.1	76.7	0.7	50.0	1.5	78.7	0.6
Forest	18.0	-	18.0	-	18.0	-	18.0
Trees	13.4	-	13.4	-	13.4	-	13.4
Shrub	0.9	-	0.9	-	0.9	-	0.9
Harvested	7.1	76.7	1.7	50.0	3.6	78.7	1.5
Wetland	4.1	-	4.1	-	4.1	-	4.1
Barren	1.3	76.7	0.3	79.2	0.3	78.7	0.3
Turfgrass	238.6	76.7	55.6	79.2	49.6	78.7	50.8
Developed Pervious	4.7	76.7	1.1	79.2	1.0	78.7	1.0
Developed Impervious	394.1	76.7	91.8	79.2	82.0	78.7	83.9
Streambank Erosion	118.2	76.7	27.6	79.2	24.6	40.0	71.0
Septic	0.9	76.7	0.2	79.2	0.2	78.7	0.2
Groundwater	150.9	-	150.9	-	150.9	-	150.9
MS4	1,406.0	76.7	327.7	79.2	292.5	78.7	299.6
Construction Permits	58.2	-	58.2	-	58.2	-	58.2
Future Growth (2%)	18.1	-	18.1	-	18.1	-	18.1
MOS (10%)	90.5	-	90.5	-	90.5	-	90.5
TOTAL	**2,720.0**	**66.8**	**904.0**	**66.8**	**903.0**	**66.8**	**903.0**

Table 6-27. Allocation scenarios for Rohoic Creek phosphorus loads. Scenario 2 does not meet target reductions.

Rohoic Creek Watershed		Scenario 1 (preferred)		Scenario 2	
Source	**Existing TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**
Cropland	31.3	98.8	0.4	100.0	-
Hay	113.1	98.8	1.4	100.0	-
Pasture	4.1	98.8	0.0	100.0	-
Forest	9.7	-	9.7	-	9.7
Trees	14.3	-	14.3	-	14.3
Shrub	1.5	-	1.5	-	1.5
Harvested	1.2	98.8	0.0	100.0	-
Wetland	2.6	-	2.6	-	2.6
Barren	-	-	-	-	-
Turfgrass	290.9	98.8	3.5	100.0	-
Developed Pervious	9.7	98.8	0.1	100.0	-
Developed Impervious	437.4	98.8	5.2	100.0	-
Streambank Erosion	86.5	98.8	1.0	100.0	-
Septic	0.9	98.8	0.0	100.0	-
Groundwater	122.3	-	122.3	-	122.3
NMMM Permits	85.3	-	85.3	-	85.3
Concrete Facility Permits	31.0	-	31.0	-	31.0
ISW Permits	394.1	50.0	197.0	-	394.1
MS4	523.4	98.8	6.3	100.0	-
Construction Permits	94.0	-	94.0	-	94.0
Future Growth (2%)	13.1	-	13.1	-	13.1
MOS (10%)	65.4	-	65.4	-	65.4
TOTAL	**2,330.0**	**71.9**	**654.0**	**64.2**	**833.0**

Table 6-28. Allocation scenarios for Swift Creek phosphorus loads (inclusive of Nuttree Branch).

Swift Creek Watershed		Scenario 1 (preferred)		Scenario 2		Scenario 3	
Source	**Existing TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**	**Reduction (%)**	**Allocation TP (lb/yr)**
Cropland	70.9	73.2	19.0	25.0	53.2	82.2	12.6
Hay	362.6	73.2	97.2	25.0	271.9	82.2	64.5
Pasture	190.9	73.2	51.2	25.0	143.2	82.2	34.0
Forest	143.3	-	143.3	-	143.3	-	143.3
Trees	115.1	-	115.1	-	115.1	-	115.1
Shrub	2.5	-	2.5	-	2.5	-	2.5
Harvested	22.6	73.2	6.1	25.0	16.9	82.2	4.0
Wetland	7.9	-	7.9	-	7.9	-	7.9
Barren	43.7	73.2	11.7	75.3	10.8	82.2	7.8
Turfgrass	1,267.0	73.2	339.5	75.3	312.9	82.2	225.5
Developed Pervious	35.3	73.2	9.5	75.3	8.7	82.2	6.3
Developed Impervious	4,237.0	73.2	1,135.0	75.3	1,046.0	82.2	754.1
Streambank Erosion	4,383.0	73.2	1,175.0	75.3	1,083.0	50.0	2,191.0
Septic	17.4	73.2	4.7	75.3	4.3	82.2	3.1
Groundwater	1,588.0	-	1,588.0	-	1,588.0	-	1,588.0
VA0006254	9.6	-	9.6	-	9.6	-	9.6
VA0023426	46.0	-	46.0	-	46.0	-	46.0
NMMM Permits	121.8	-	121.8	-	121.8	-	121.8
Domestic Sewage Permits	17.2	-	17.2	-	17.2	-	17.2
ISW Permits	377.1	-	377.1	-	377.1	-	377.1
MS4	5,071.0	73.2	1,359.0	75.3	1,253.0	82.2	902.7
Construction Permits	1,040.0	-	1,040.0	-	1,040.0	-	1,040.0
Future Growth (2%)	174.6	-	174.6	-	174.6	-	174.6
MOS (10%)	873.0	-	873.0	-	873.0	-	873.0
TOTAL	**20,200.0**	**56.8**	**8,730.0**	**56.8**	**8,720.0**	**56.8**	**8,720.0**

7.0 TMDL IMPLEMENTATION AND REASONABLE ASSURANCE

7.1. Regulatory Framework

There is a regulatory framework in place to help enforce the development and attainment of TMDLs and their stated goals on both the federal and the state level in Virginia. On the federal level, section 303(d) of the Clean Water Act and current USEPA regulations, while not explicitly requiring the development of TMDL implementation plans as part of the TMDL process, do require reasonable assurance that the load and waste load allocations can and will be implemented. Federal regulations also require that all new or revised National Pollutant Discharge Elimination System (NPDES) permits must be consistent with the assumptions and requirements of any applicable TMDL WLA (40 CFR §122.44 (d)(1)(vii)(B)).

At the state level, Virginia’s 1997 Water Quality Monitoring, Information and Restoration Act (WQMIRA) directs the State Water Control Board to “develop and implement a plan to achieve fully supporting status for impaired waters” (Section 62.1-44.19.7). WQMIRA also establishes that the implementation plan shall include the date of expected achievement of water quality objectives, measurable goals, corrective actions necessary and the associated costs, benefits and environmental impacts of addressing the impairments. After DEQ approves the TMDL study, staff will present the study to the State Water Control Board (SWCB) and request that the SWCB adopt TMDL WLAs as part of the Water Quality Management Planning Regulation (9 VAC 25-270), in accordance with §2.2-4006A.14 and §2.2-4006B of the Code of Virginia. DEQ-s public participation procedures relating to TMDL development can be found in DEQ’s Guidance Memo No.14-2016 (VADEQ, 2014).

VADEQ regulates stormwater discharges associated with industrial activities through its VPDES program and stormwater discharges from construction sites and MS4s through its VSMP program. All new or revised permits must be consistent with the assumptions and requirements of any applicable TMDL WLA.

7.2. Implementation Plans

Implementation plans set intermediate goals and describe actions (with associated costs) that can be taken to clean up impaired streams. Some of the actions that may be included in an implementation plan to address excess sediment and phosphorus include:

- Fence out cattle from streams and provide alternative water sources
- Implement conservation tillage practices on cropland
- Conduct stream bank restoration projects in areas where banks are actively eroding

- Leave a band of 35 – 100 ft along the stream natural so that it buffers or filters out sediment from farm or residential land (a riparian buffer)
- Expand street sweeping programs in urban areas
- Install and/or retrofit urban stormwater BMPs
- Reduce runoff by increasing green spaces and reducing hardened spaces (asphalt or concrete)

Overall, implementation of TMDLs works best with a targeted, staged approach, directing initial efforts where the biggest impacts can be made with the least effort so that money, time, and other resources are spent efficiently to maximize the benefit to water quality. Progress towards meeting water quality goals defined in the implementation plan will be assessed during implementation by the tracking of new BMP installations and continued water quality monitoring by VADEQ. Several BMPs have already been implemented in the watershed and were accounted for in the development of this TMDL (**Section 4.4**).

Implementation plans also identify potential sources of funding to help in the clean-up efforts. Funds are often available in the form of cost-share programs, which share the cost of improvements with the landowner. Potential sources of funding include USEPA Section 319 funding for Virginia's Nonpoint Source Management Program, the USDA's Conservation Reserve Enhancement Program (CREP) and its Environmental Quality Incentive Program (EQIP), the Virginia State Revolving Loan Program, and the Virginia Water Quality Improvement Fund. The Virginia Guidance Manual for Total Maximum Daily Load Implementation Plans (VADEQ, 2017) contains information on a variety of funding sources, as well as government agencies that might support implementation efforts and suggestions for integrating TMDL implementation with other watershed planning efforts. Additional sources are also often available for specific projects and regions of the state. State agencies and other stakeholders may help identify funding sources to support the plan, but implementing the improvements is up to those that live in the watershed. Part of the purpose of developing a TMDL and implementation plan is to increase education and awareness of the water quality issues in the watershed and encourage residents and stakeholders to work together to improve the watershed.

7.3. Reasonable Assurance

The following activities provide reasonable assurance that these TMDLs will be implemented and water quality will be restored in the James River Tributaries watersheds.

- Regulatory frameworks – Existing federal and state regulations require that new and existing permits comply with the developed TMDLs. State law also requires that implementation plans be developed to meet TMDL goals.
- Funding sources – Numerous funding sources (listed above) are available to defray the cost of TMDL implementation.

- Public participation – Public participation in the TMDL process informs and mobilizes watershed residents and stakeholders to take the necessary actions to implement the TMDL.
- Continued monitoring – Water quality and aquatic life monitoring will continue in the TMDL watersheds and track progress towards the TMDL goals. VADEQ will continue monitoring benthic macroinvertebrates and habitat in accordance with its biological monitoring program stations throughout the watershed.
- MS4 permit local TMDL action plans – In addition to developing action plans to address Chesapeake Bay TMDL requirements, MS4 permit holders are required to develop and implement action plans for local TMDLs to reduce pollutant loadings to local streams in addition to the Chesapeake Bay watershed. These reductions will help to improve local water quality in the James River tributaries as well as in the Chesapeake Bay.
- Current implementation actions – Many voluntary and subsidized best management practices have already been installed in these watersheds. The Soil and Water Conservation Districts and NRCS are actively working in these areas to promote and implement additional practices that can reduce sediment and phosphorus loads.

8.0 PUBLIC PARTICIPATION

Public participation was solicited at every stage of the TMDL development in order to receive input from stakeholders and to apprise the stakeholders of the progress made. A series of three Technical Advisory Committee (TAC) meetings took place during model and allocation development. The TAC included representatives from Chesterfield County, Chesterfield County School Board, John Tyler Community College, VDOT, the James River Association, CE&H Heritage Civic League, Addison Evans Water Production and Lab Facility, Aleris, Ashland Special Ingredients G.P., Branscome Incorporated, Dominion Energy, International Paper, LaBella Associates, Martin Marietta Materials, Inc., and Troutman Pepper in representation of the VA Manufacturers Association. Due to the State of Emergency related to the COVID-19 pandemic at the time, the first public meeting and first two TAC meetings were held virtually. The virtual meetings were recorded and posted on the DEQ website for increased accessibility.

The first public meeting (46 attendees, January 26th, 2021) was held virtually. This meeting introduced attendees to DEQ's water quality planning process, the TMDL purpose and process, reviewed benthic monitoring data collected from the study watersheds, discussed the impairments, and reviewed the preliminary results of the stressor analysis.

The first TAC meeting (24 attendees, February 3rd, 2021) was held virtually to discuss the draft of the Benthic Stressor Analysis and the CADDIS results, and to outline the next steps in the study process.

The second TAC meeting (22 attendees, April 14th, 2021) was held virtually. This meeting discussed the development of the GWLF models, source assessment and permits, and the All Forested Load Multiplier methodology.

The third TAC meeting (11 attendees, May 9th, 2022) was held in the Clover Hill Library in Midlothian, VA. This meeting reviewed permitted sources, the modeling approach, and endpoints developed using AllForX. Multiple allocation scenarios to achieve the target loads were presented. Committee members then voted on the allocation scenario that would be implemented in the TMDL for each creek.

A final public meeting was held on February 15, 2023 at the Clover Hill Library in Midlothian, VA to present the draft TMDL document. The public meeting marked the beginning of the official public comment period and was attended by ## watershed residents and other stakeholders. The public comment period ended on March 17, 2023.

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Appendix A - GWLF Model Parameters

Various GWLF parameters used for the James River tributaries TMDL models are detailed below. **Table A-1** and **Table A-2** list the various watershed-wide parameters. The land use parameters for the watersheds are listed in **Table A-3** through **Table A-8**.

Table A-1. Watershed-wide GWLF parameters.

GWLF Parameter	Units	Value
Recession Coefficient	day^{-1}	0.21
Seepage Coefficient	day^{-1}	0.16
Leakage Coefficient	day^{-1}	0.075
Erosivity Coefficient (Nov-Mar)		0.15
Erosivity Coefficient (Apr-Oct)		0.3
Sediment P Concentration	mg/kg	700
Groundwater P Concentration	mg/L	0.013
Septic System Effluent P	g/person-day	1.37
Plant Nutrient Uptake P	g/person-day	0.4

Table A-2. Additional GWLF watershed parameters.

GWLF Parameter	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek
Sediment Delivery Ratio	0.15	0.20	0.16	0.14	0.17	0.08
Unsaturated Water Capacity (cm)	21.77	19.65	20.86	20.35	21.99	20.20
aFactor	0.0002927	0.0003544	0.0002234	0.0003404	0.0002925	0.0001864
Total Stream Length (m)	24542	7319	28447	34308	21265	167230
Mean Channel Depth (m)	2.57	1.85	2.51	2.86	2.21	5.48
ET Cover Coefficient, Apr-Oct	0.896	0.820	0.915	0.821	0.869	0.913
ET Cover Coefficient, Nov-Mar	0.824	0.747	0.818	0.768	0.801	0.809

Table A-3. Pervious land cover parameters for Bailey Creek.

Land Cover	Area (ha)	CN	KLSCP	Runoff P (mg/L)	Sediment Build-up (kg/ha-d)	P in Sediment Build-up (kg/kg)
High_till	0.5	82.5	0.02699	0.18	n/a	n/a
Low_till	55.4	78.5	0.00328	0.141	n/a	n/a
Hay	80.7	68.1	0.00085	0.2	n/a	n/a
Pasture_Good	0.0	0.0	0	0.2	n/a	n/a
Pasture_Fair	3.7	76.8	0.00846	0.51	n/a	n/a
Pasture_Poor	1.0	84.4	0.01501	0.82	n/a	n/a
Forest	1100.2	66.4	0.00057	0.01	n/a	n/a
Trees	607.7	69.8	0.00536	0.03	n/a	n/a
Shrub	53.4	56.4	0.00486	0.03	n/a	n/a
Harvested Forest	35.8	71.2	0.00924	0.05	n/a	n/a
Water	6.9	98.0	0	0	n/a	n/a
Wetland	166.9	73.3	0.00394	0	n/a	n/a
Barren	7.3	76.0	0.22212	0.05	n/a	n/a
Turfgrass	962.2	71.3	0.00115	0.38	n/a	n/a
Developed pervious	80.7	71.0	0.00275	0.25	n/a	n/a
Developed impervious	322.8	98.0	0	n/a	6.2	0.00217
Impervious local dataset	204.8	98.0	0	n/a	2.8	0.00217

Table A-4. Pervious land cover parameters for Nuttree Branch.

Land Cover	Area (ha)	CN	KLSCP	Runoff P (mg/L)	Sediment Build-up (kg/ha-d)	P in Sediment Build-up (kg/kg)
High_till	0.0	0.0	0	0.18	n/a	n/a
Low_till	0.0	0.0	0	0.141	n/a	n/a
Hay	0.0	0.0	0	0.2	n/a	n/a
Pasture_Good	0.0	0.0	0	0.2	n/a	n/a
Pasture_Fair	0.0	0.0	0	0.51	n/a	n/a
Pasture_Poor	0.0	0.0	0	0.82	n/a	n/a
Forest	418.2	69.3	0.00035	0.01	n/a	n/a
Trees	335.4	72.4	0.00422	0.03	n/a	n/a
Shrub	15.6	59.8	0.00623	0.03	n/a	n/a
Harvested Forest	0.0	0.0	0	0.05	n/a	n/a
Water	17.1	98.0	0	0	n/a	n/a
Wetland	11.6	74.9	0.00241	0	n/a	n/a
Barren	0.0	0.0	0	0.05	n/a	n/a
Turfgrass	385.2	72.0	0.00129	0.38	n/a	n/a
Developed pervious	13.0	74.2	0.00325	0.25	n/a	n/a
Developed impervious	52.2	98.0	0	n/a	6.2	0.00217
Impervious local dataset	260.5	98.0	0	n/a	2.8	0.00217

Table A-5. Pervious land cover parameters for Oldtown Creek.

Land Cover	Area (ha)	CN	KLSCP	Runoff P (mg/L)	Sediment Build-up (kg/ha-d)	P in Sediment Build-up (kg/kg)
High_till	27.5	83.4	0.02151	0.18	n/a	n/a
Low_till	226.1	79.4	0.00261	0.141	n/a	n/a
Hay	97.5	67.9	0.00062	0.2	n/a	n/a
Pasture_Good	0.0	0.0	0	0.2	n/a	n/a
Pasture_Fair	0.0	0.0	0	0.51	n/a	n/a
Pasture_Poor	1.0	84.3	0.01094	0.82	n/a	n/a
Forest	1135.2	71.5	0.00028	0.01	n/a	n/a
Trees	404.0	71.9	0.00315	0.03	n/a	n/a
Shrub	12.5	69.3	0.00392	0.03	n/a	n/a
Harvested Forest	54.6	74.9	0.00372	0.05	n/a	n/a
Water	23.9	98.0	0	0	n/a	n/a
Wetland	203.0	75.8	0.00172	0	n/a	n/a
Barren	0.7	71.0	0.1364	0.05	n/a	n/a
Turfgrass	808.4	72.6	0.0006	0.38	n/a	n/a
Developed pervious	40.4	73.5	0.00231	0.25	n/a	n/a
Developed impervious	161.7	98.0	0	n/a	6.2	0.00217
Impervious local dataset	257.4	98.0	0	n/a	2.8	0.00217

Table A-6. Pervious land cover parameters for Proctors Creek.

Land Cover	Area (ha)	CN	KLSCP	Runoff P (mg/L)	Sediment Build-up (kg/ha-d)	P in Sediment Build-up (kg/kg)
High_till	0.2	83.6	0.01724	0.18	n/a	n/a
Low_till	30.7	79.6	0.00209	0.141	n/a	n/a
Hay	25.4	69.6	0.00115	0.2	n/a	n/a
Pasture_Good	0.0	0.0	0	0.2	n/a	n/a
Pasture_Fair	2.8	77.9	0.01146	0.51	n/a	n/a
Pasture_Poor	0.0	0.0	0	0.82	n/a	n/a
Forest	979.1	71.7	0.00035	0.01	n/a	n/a
Trees	975.4	70.6	0.00344	0.03	n/a	n/a
Shrub	28.5	63.0	0.00359	0.03	n/a	n/a
Harvested Forest	0.0	0.0	0	0.05	n/a	n/a
Water	33.7	98.0	0	0	n/a	n/a
Wetland	326.2	74.1	0.00213	0	n/a	n/a
Barren	17.7	79.7	0.10152	0.05	n/a	n/a
Turfgrass	1403.2	71.2	0.00089	0.38	n/a	n/a
Developed pervious	36.3	70.9	0.00288	0.25	n/a	n/a
Developed impervious	145.3	98.0	0	n/a	6.2	0.00217
Impervious local dataset	871.9	98.0	0	n/a	2.8	0.00217

Table A-7. Pervious land cover parameters for Rohoic Creek.

Land Cover	Area (ha)	CN	KLSCP	Runoff P (mg/L)	Sediment Build-up (kg/ha-d)	P in Sediment Build-up (kg/kg)
High_till	6.5	84.7	0.02318	0.18	n/a	n/a
Low_till	53.1	80.7	0.00282	0.141	n/a	n/a
Hay	109.6	69.6	0.00116	0.2	n/a	n/a
Pasture_Good	0.0	0.0	0	0.2	n/a	n/a
Pasture_Fair	0.0	0.0	0	0.51	n/a	n/a
Pasture_Poor	1.1	85.2	0.02058	0.82	n/a	n/a
Forest	702.8	69.9	0.00033	0.01	n/a	n/a
Trees	340.7	70.6	0.00445	0.03	n/a	n/a
Shrub	24.5	64.3	0.00453	0.03	n/a	n/a
Harvested Forest	7.2	77.0	0.00365	0.05	n/a	n/a
Water	22.8	98.0	0	0	n/a	n/a
Wetland	76.1	71.7	0.0022	0	n/a	n/a
Barren	0.0	0.0	0	0.05	n/a	n/a
Turfgrass	672.9	72.8	0.00103	0.38	n/a	n/a
Developed pervious	28.4	72.9	0.00298	0.25	n/a	n/a
Developed impervious	113.8	98.0	0	n/a	6.2	0.00217
Impervious local dataset	284.2	98.0	0	n/a	2.8	0.00217

Table A-8. Pervious land cover parameters for Swift Creek.

Land Cover	Area (ha)	CN	KLSCP	Runoff P (mg/L)	Sediment Build-up (kg/ha-d)	P in Sediment Build-up (kg/kg)
High_till	19.5	82.9	0.03859	0.18	n/a	n/a
Low_till	166.6	78.9	0.00469	0.141	n/a	n/a
Hay	490.5	66.3	0.00098	0.2	n/a	n/a
Pasture_Good	22.6	70.1	0.00251	0.2	n/a	n/a
Pasture_Fair	171.1	76.0	0.01004	0.51	n/a	n/a
Pasture_Poor	16.5	83.9	0.0179	0.82	n/a	n/a
Forest	14107.1	66.6	0.00039	0.01	n/a	n/a
Trees	3988.4	68.3	0.004	0.03	n/a	n/a
Shrub	120.0	58.1	0.00621	0.03	n/a	n/a
Harvested Forest	192.8	76.1	0.00486	0.05	n/a	n/a
Water	829.8	98.0	0	0	n/a	n/a
Wetland	769.4	75.1	0.00249	0	n/a	n/a
Barren	61.4	78.9	0.20792	0.05	n/a	n/a
Turfgrass	4179.0	70.6	0.00115	0.38	n/a	n/a
Developed pervious	176.1	70.4	0.00346	0.25	n/a	n/a
Developed impervious	704.6	98.0	0	n/a	6.2	0.00217
Impervious local dataset	2079.4	98.0	0	n/a	2.8	0.00217

Appendix B - Sensitivity Analysis

Analyses were conducted to assess the sensitivity of the model to changes in hydrologic and water quality parameters, as well as to assess the potential impact of uncertainty in parameter determination. Sensitivity analyses were run for each study watershed on the parameters listed in **Table A-1** through **Table A-8**, which served as the baseline value for each watershed. The outputs from model runs using the listed base parameter values were compared to model runs changing each of the parameters by +10% and -10% of the base value. The results are shown in **Table B-1**.

The relationships exhibit linear responses except for sediment response to changes in curve numbers. Changes in variables specific to sediment such as KLSCP had no impact on hydrology, which was to be expected. Sediment related parameters impacted phosphorus loads, but phosphorus-specific parameters such as the concentration of phosphorus in soil only affected phosphorus loads. Changes in curve numbers had the most influence on both the flow and pollutant loads. Changes in other hydrologic parameters had more impact on runoff volume than on sediment load, with the seepage and recession coefficients having the next largest impacts on hydrology after curve number and ET-CV.

Table B-1. Results of the GWLF sensitivity analysis, averaged across all watersheds.

Model Parameter	Parameter Change (%)	Total Runoff Volume Change (%)	Total Sediment Load Change (%)	Total Phosphorus Load Change (%)
CN	+10	12.9%	17.6%	32.6%
	-10	-12.3%	-23.0%	-32.9%
KLSCP	+10	0.0%	4.4%	0.4%
	-10	0.0%	-4.4%	-0.4%
Runoff P	+10	0.0%	0.0%	3.1%
	-10	0.0%	0.0%	-3.1%
Sediment Build-up	+10	0.0%	2.4%	4.1%
	-10	0.0%	-2.4%	-4.1%
P in Sediment Build-up	+10	0.0%	0.0%	3.8%
	-10	0.0%	0.0%	-3.8%
Recession Coefficient	+10	2.3%	0.4%	0.6%
	-10	-2.6%	-0.5%	-0.7%
Seepage Coefficient	+10	-2.3%	-0.5%	-0.6%
	-10	2.5%	0.5%	0.7%
Leakage Coefficient	+10	0.6%	0.2%	0.2%
	-10	-0.6%	-0.2%	-0.2%
AWC	+10	-0.4%	-0.1%	-0.1%
	-10	0.6%	0.2%	0.2%
ET-CV	+10	-6.9%	-1.5%	-2.0%
	-10	8.1%	1.8%	2.3%

Appendix C - AllForX Development

The method used to set TMDL endpoint loads for the James River Tributaries is called the "all-forest load multiplier" (AllForX) approach, introduced in **Section 5.0**. AllForX is the ratio calculated by dividing the simulated pollutant load under existing conditions by the pollutant load from an all-forest simulated condition for the same watershed. In other words, AllForX is an indication of how much higher current sediment loads are above an undeveloped condition. After calculating AllForX values for a range of monitoring stations (**Table C-1**), a regression is developed between the AllForX values and corresponding VSCI scores at those stations (**Figure C-1** and **Figure C-2**). This relationship between AllForX values and VSCI scores can be used to quantify the AllForX value that corresponds to the VSCI threshold score of 60.

These multipliers were calculated for a total of 15 watersheds of similar size and within the same ecoregion as the TMDL watersheds (**Figure C-3**). These watersheds included both unimpaired and impaired streams to represent a wide distribution of current conditions. Watersheds used in developing the VSCI and AllForX regression were selected to be similar in size and located near the study watersheds to minimize differences in flow regime, soils, and other physiographic properties. Additionally, the watersheds must have adequate and recent VSCI data for a watershed to be a useful data point.

For the purposes of building the AllForX regression, permitted sources were not included. This was to leave the flexibility of potentially incorporating other watersheds into the regression that may have less available data and be able to compare the trends more fairly. The same set of watershed models were run a second time, changing all of the land use parameters to reflect forested land cover while preserving the unique soil and slope characteristics of each watershed. The AllForX value was calculated for each modeled watershed by dividing the original model loads by the all-forested model loads. This data is presented in **Table C-1**.

A regression was then developed between the Virginia Stream Condition Index (VSCI) scores at monitoring stations and the corresponding AllForX value calculated for the watershed draining to each station. The regression for sediment (TSS) resulted in an R^2 value of 0.373, and the regression for phosphorus (TP) resulted in an R^2 value of 0.422. These regressions were used to quantify the values of AllForX corresponding to the benthic health threshold (VSCI = 60) for sediment and phosphorus. Based on the regressions, a VSCI score of 60 corresponded to a target AllForX value of 5.85 for sediment and 3.36 for phosphorus. This means that the TMDL streams are expected to achieve consistently healthy benthic conditions if sediment loads are less than 5.85 times the simulated load of an all-forested watershed, and phosphorus less than 3.36 times the all-forested load. The allowable sediment or phosphorus TMDL load was then calculated by applying the AllForX threshold where VSCI = 60 (5.85 for TSS or 3.36 for TP) to the All-Forest simulated pollutant load of the target watershed to determine the final target TMDL loading. An explicit margin of safety was implemented based on this target loading rate, setting aside 10% of the allowable load specifically for the margin of safety.

Table C-1. Model run results for AllForX value development.

Station ID	VASCI avg	TSS (t/yr)	TSS All-Forested (lb/yr)	TSS Multiplier	TP (lb/yr)	TP All-Forested (lb/yr)	TP Multiplier
2-BLY005.73	32.0	300	23	12.9	2,104.0	81.1	25.9
2-OTC001.54	49.7	567	46	12.3	2,418.0	256.4	9.4
2-RHC000.58	48.8	220	25	8.8	1,559.0	88.0	17.7
2-JOH004.23	60.6	116	26	4.5	1,040.0	124.9	8.3
2-SFT012.84	71.62	11,389	1,260	9.0	22,613	3,430.5	6.6
2-SFT019.15	43.0	7,426	827	9.0	16,380.0	2,412.0	6.8
2-SFT025.32	44.7	5,588	616	9.1	13,080.0	1,857.0	7.0
2-NUT000.62	51.4	245	29	8.5	1,199.0	104.4	11.5
2-OTC005.38	50.8	222	23	9.6	993.9	133.0	7.5
2DTRO001.88	67.2	172	29	5.8	860.8	141.7	6.1
2-PCT002.46	49.3	958	65	14.7	4,077.0	291.0	14.0
2-SFT019.02	48.0	7,646	845	9.0	16,770.0	2,459.0	6.8
2-LIA000.50	56.4	665	106	6.3	2,619.0	611.5	4.3
2-FIN000.81	58.8	504	67	7.6	2,338.0	449.9	5.2
2-NWD004.15	64.0	387	61	6.4	1,996.0	426.8	4.7

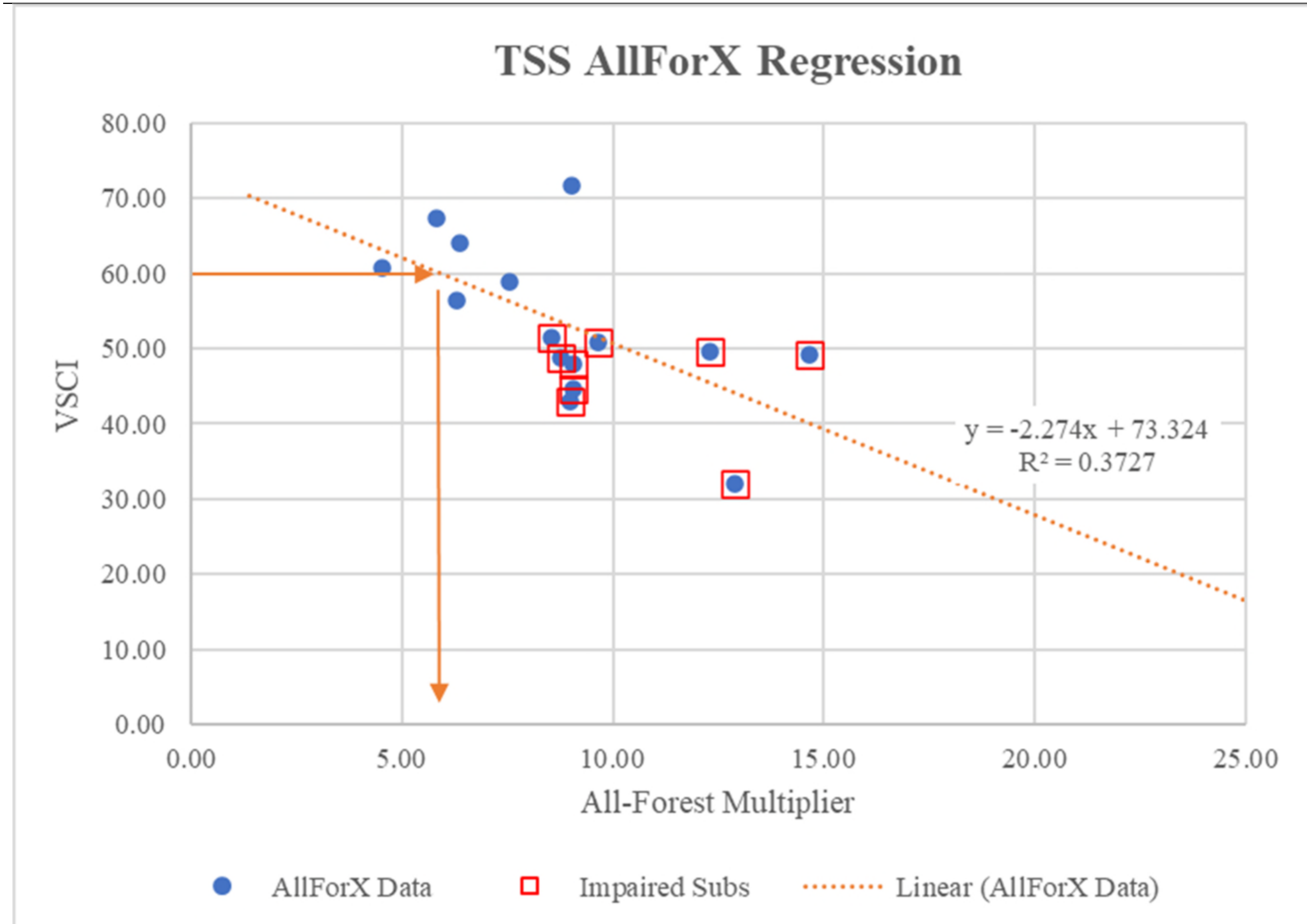

Figure C-1. Regression for sediment in the James River tributaries TMDL, resulting AllForX target value of 5.85.

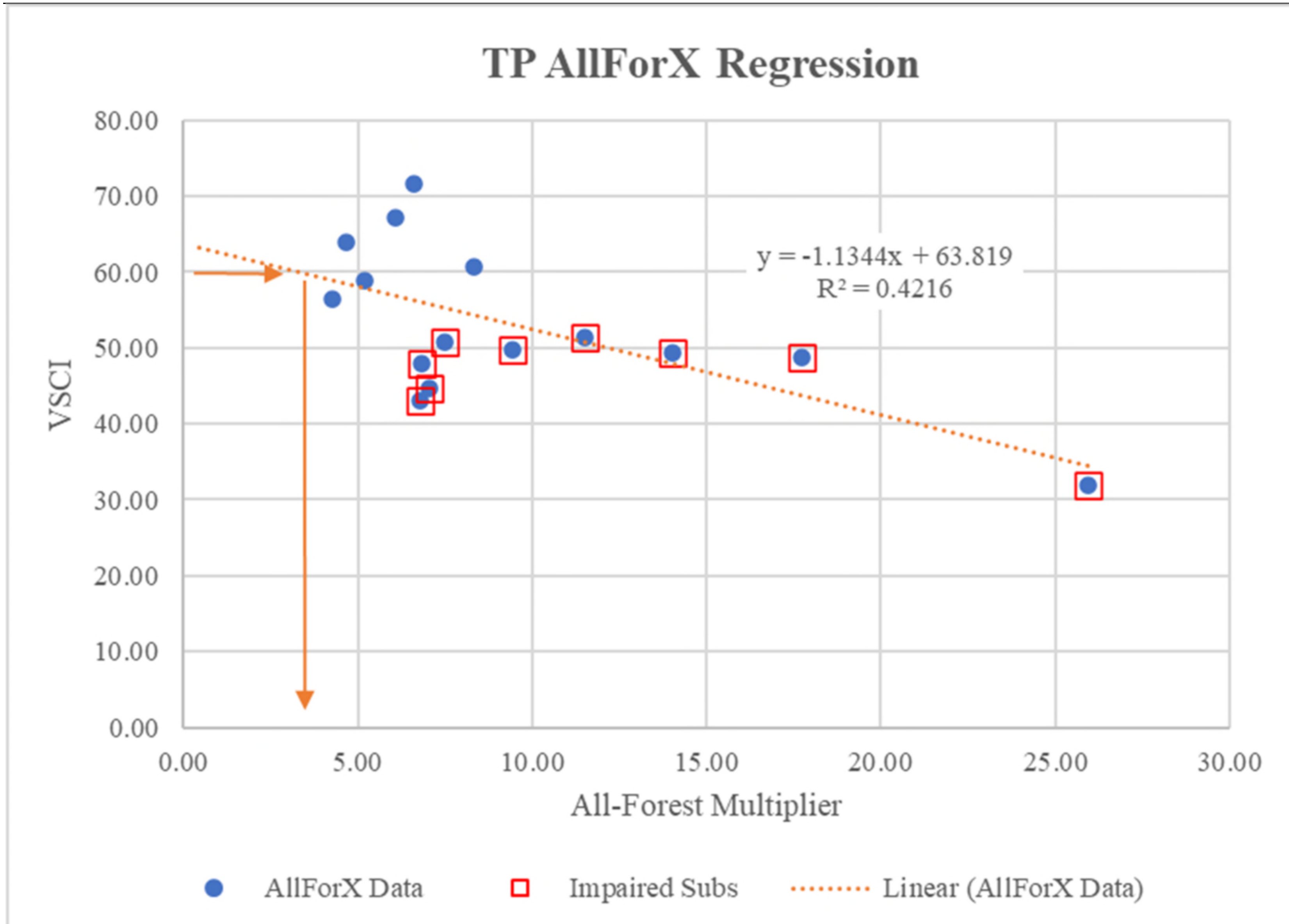

Figure C-2. Regression for Phosphorus in the James River tributaries TMDL, resulting AllForX target value of 3.36.

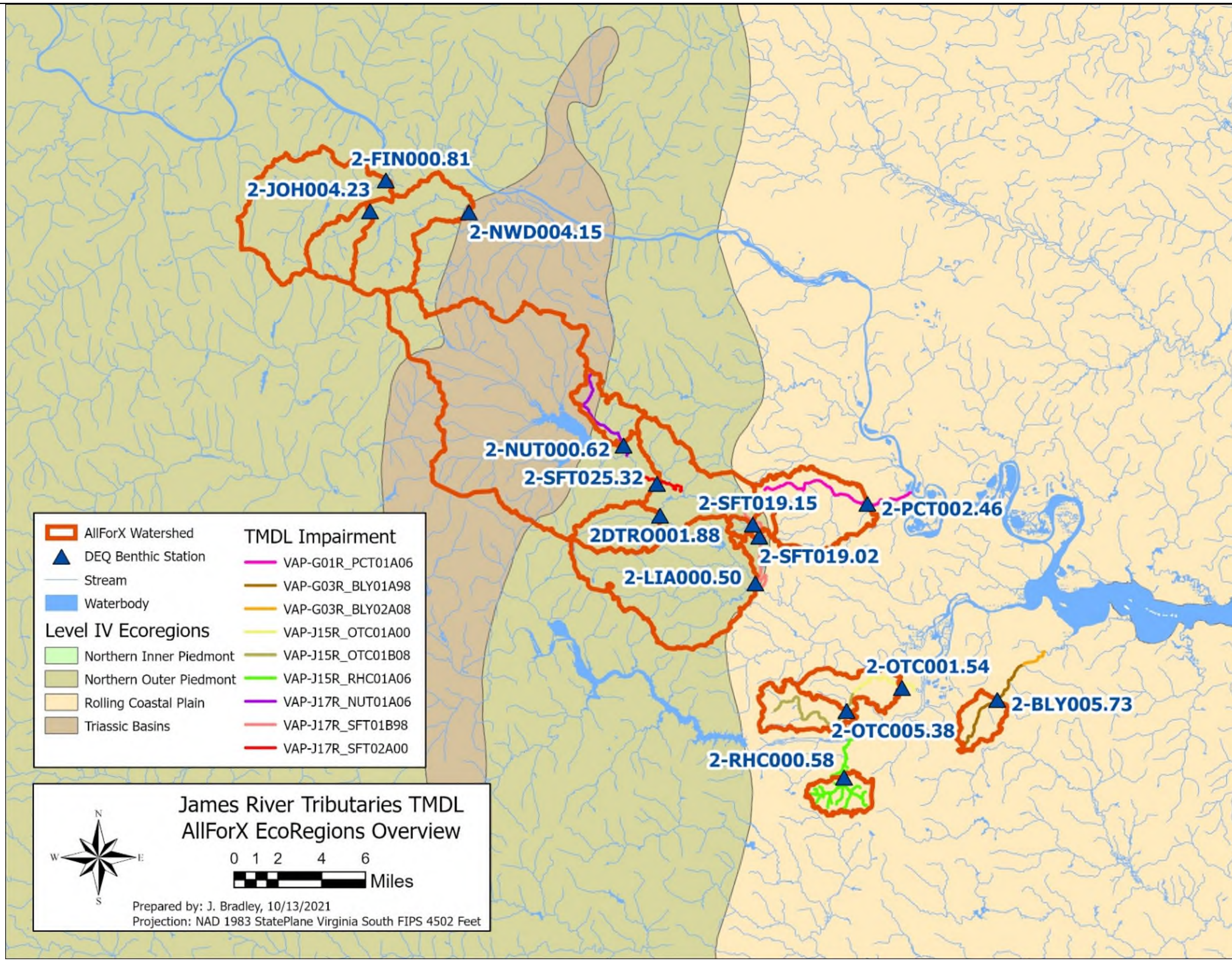

Figure C-3. Location of James River tributaries AllForX TMDL watersheds and ecoregions .

Appendix D - Stressor Identification Analysis Report

Stressor Identification Analysis for the James River Tributaries

Prepared by:
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Prepared for:
Virginia Department of Environmental Quality

March 2021

EEE Consulting, Inc.
Environmental, Engineering and Educational Solutions

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Acronyms

BCG	Biological Condition Gradient
CADDIS	Causal Analysis/Diagnosis Decision Information System
CCU	Cumulative Criterion Unit
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
EIS	Environmental Impact Statement
EPT	Ephemeroptera, Plecoptera, Trichoptera
JMU	James Madison University
LRBS	Log Relative Bed Stability Index
MFBI	Modified Family Biotic Index
NWBD	National Watershed Boundary Dataset
PAHs	Polycyclic Aromatic Hydrocarbons
PCBs	Polychlorinated Biphenyls
PEC	Probable Effect Concentration
SCI	Virginia Stream Condition Index
TDS	Total Dissolved Solids
TEC	Threshold Effect Concentration
TOC	Total Organic Carbon
TRV	Toxicity Reference Value
TSS	Total Suspended Solids
TVS	Total Volatile Solids
USEPA	U.S. Environmental Protection Agency
VDEQ	Virginia Department of Environmental Quality

Executive Summary

This Stressor Identification Analysis Report addresses benthic impairments in Bailey Creek, Nuttree Branch, Oldtown Creek, Proctors Creek, Rohoic Creek, and Swift Creek (collectively called the James River Tributaries Project). The analysis was conducted in accordance with the U.S. Environmental Protection Agency's (USEPA) Stressor Identification Guidance Document (USEPA, 2000b) using the Causal Analysis/Diagnosis Decision Information System (CADDIS) (USEPA, 2018a). Twenty years of data (2000 – 2020) on over 360 parameters from 49 monitoring stations totaling over 130,000 data points were used in the analysis. These data were evaluated according to 18 lines of evidence to categorize candidate stressors as non-stressors, possible stressors, or probable stressors. Based on the evaluation, sediment was identified as a probable stressor in each of the six streams, and phosphorus was identified as a probable stressor in Oldtown Creek, Rohoic Creek, and Swift Creek. As a result, sediment and phosphorus TMDLs should be developed to address these probable stressors and associated impairments. In addition, dissolved oxygen was a probable stressor in Oldtown Creek and Swift Creek, and pH was a probable stressor in Oldtown Creek and Proctors Creek. The pH stressor in Oldtown Creek and Proctors Creek was determined to be due to natural conditions resulting from the decay of organic matter in connected wetlands and the production of natural organic acids. The dissolved oxygen stressor in Oldtown Creek and Swift Creek is associated with increased nutrients and other contributing factors, so it will be addressed through the phosphorus TMDL. Specifically in the stream segment just below Swift Creek Reservoir, DEQ will be collecting additional dissolved oxygen data and would likely pursue a Category 4C Assessment (impaired but not needing a TMDL) if the dissolved oxygen issue is determined to be solely caused by either naturally occurring conditions or the dam on Swift Creek Reservoir.

1.0 OVERVIEW

1.1. Benthic Impairments

The Virginia Department of Environmental Quality (VDEQ) contracted EEE Consulting, Inc. and James Madison University (JMU) to conduct a stressor identification analysis for benthic impairments in the James River watershed in Chesterfield, Dinwiddie, and Prince George Counties, including the Cities of Petersburg and Hopewell. The six impaired streams (and nine corresponding assessment units) are listed in Table 1, shown in Figure 1, and collectively referred to as the James River Tributaries Project. This project addresses benthic impairments in Bailey Creek, Nuttree Branch, Oldtown Creek, Proctors Creek, Rohoic Creek, and Swift Creek.

Table 1. Benthic impairments in the James River Tributaries Project.

Stream Name	NWBD	Impaired Assessment Units	Cause Group Code	First listed	Length (miles)	Impairment Description
Bailey Creek	JL07	VAP-G03R_BLY02A08	G03R-02-BEN	2014	1.35	Manchester Run to the tidal limit
	JL07	VAP-G03R_BLY01A98	G03R-02-BEN	2014	5.12	Headwaters to Manchester Run.
Nuttree Branch	JA42	VAP-J17R_NUT01A06	J17R-06-BEN	2012	5.58	Headwaters to mouth at Swift Creek
Oldtown Creek	JA40	VAP-J15R_OTC01A00	J15R-02-BEN	2010	4.22	Confluence with Big Branch to the fall line
	JA40	VAP-J15R_OTC01B08	J15R-08-BEN	2018	6.22	Headwaters to the confluence of Big Branch
Proctors Creek	JL03	VAP-G01R_PCT01A06	G01R-15-BEN	2010	8.26	Headwaters to tidal limit
Rohoic Creek	JA40	VAP-J15R_RHC01A06	J15R-05-BEN	2012	13.45	Headwaters to mouth at Appomattox River
Swift Creek	JA42	VAP-J17R_SFT01B98	J17R-01-BEN	2010	7.25	Swift Creek Lake dam downstream to the confluence with Licking Creek
	JA42	VAP-J17R_SFT02A00	J17R-09-BEN	2010	2.88	Reedy Branch to the limit of Swift Creek Lake

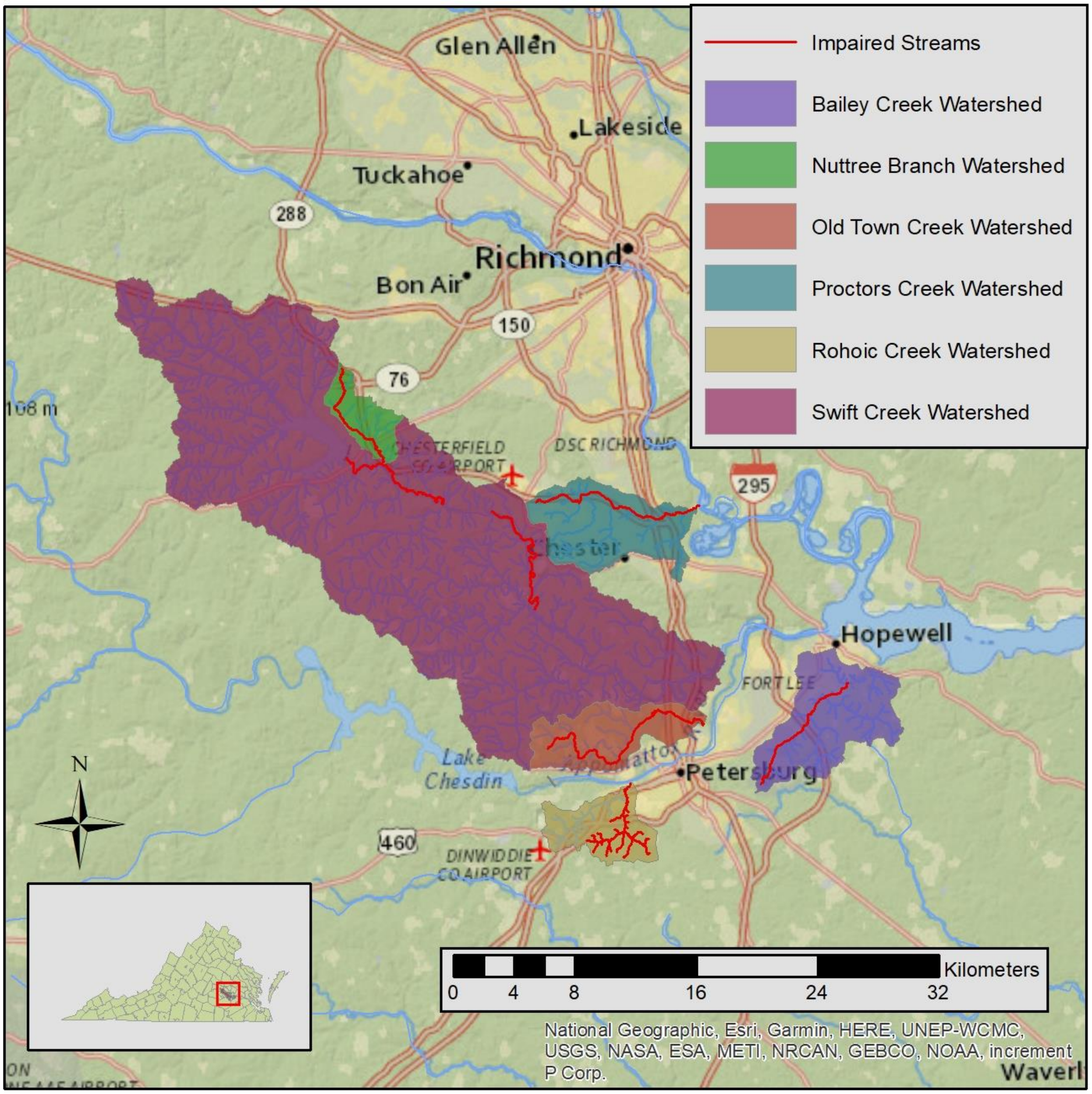

Figure 1. Location of benthic impairments in the James River Tributaries Project.

1.2. Stressor Analysis Process

Benthic impairments are based on biological assessments of the benthic community. These biological assessments are effective at determining whether a water body is impaired or not, but they do not provide information on the stressor or source causing the impairment. To determine the cause of the impairment, a stressor identification analysis must be conducted. JMU conducted this analysis according to the U.S. Environmental Protection Agency's (USEPA) Stressor Identification Guidance Document (USEPA, 2000b). In short, the stressor identification analysis identifies the pollutant(s) responsible for the benthic impairment through a weight of evidence approach that evaluates all available information on potential candidate stressors (Figure 2). The TMDL is then developed to target pollutants that are identified as the most probable stressor(s).

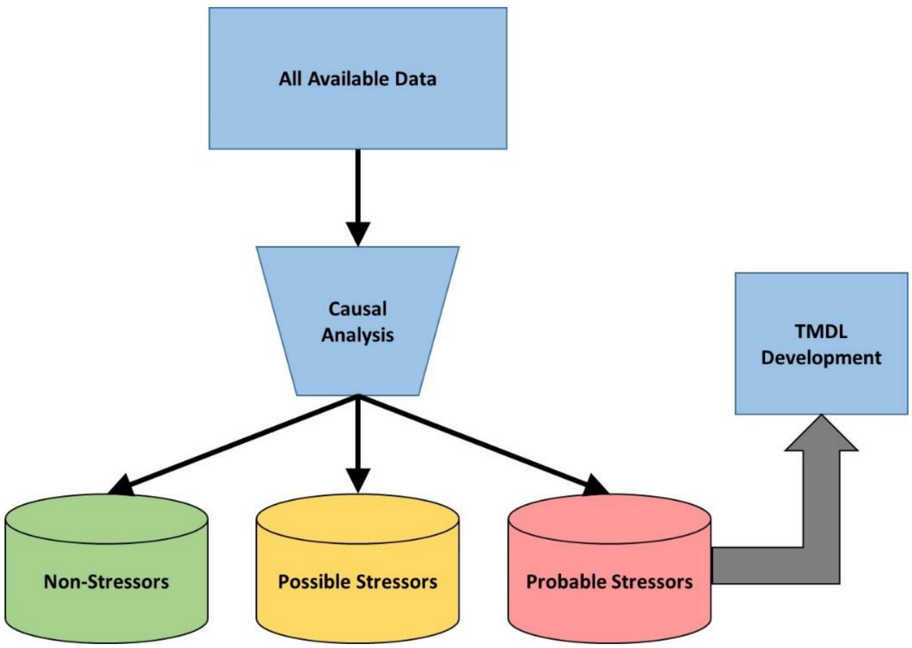

Figure 2. Stressor identification analysis process.

The first step in the stressor identification analysis is to list potential candidate stressors. JMU identified these from the listing information, monitoring data, scientific literature, and historic information. Potential stressors include both pollutants that can be targeted through TMDL development and additional contributing factors that can influence and stress benthic communities but that cannot be effectively targeted through TMDL development (Table 2).

The next step is to analyze all of the available evidence to support or eliminate potential candidate stressors. In this step, JMU used the Causal Analysis/Diagnosis Decision Information System (CADDIS) (USEPA, 2018a). The CADDIS approach provides guidance on evaluating various lines of evidence to determine the cause of biological impairments. For this project, JMU used available physical, chemical, and biological data collected throughout the watershed, published water quality standards and threshold values, and available literature from other cases to investigate the potential causes of impairment in each of the impaired streams. Based on the weight of evidence supporting each potential candidate, stressors were then separated into the following categories: non-stressor(s), possible stressor(s), and probable stressor(s).

Table 2. Candidate stressors evaluated in the James River Tributaries Project.

Candidate Pollutants		
pH	Dissolved Sulfate	Ammonia
Dissolved Oxygen	Total Dissolved Ions	Dissolved Metals
Temperature	Suspended Solids	Sediment Toxics
Conductivity	Deposited Sediment	Sediment Metals
Dissolved Chloride	Organic Matter	Pesticides
Dissolved Sodium	Nitrogen	Polycyclic Aromatic Hydrocarbons (PAHs)
Dissolved Potassium	Phosphorus	Polychlorinated Biphenyls (PCBs)
Additional Contributing Factors		
Habitat	Hydrologic Alteration	Existing Dams and Impoundments
Natural Low Gradient	Current Land Use Practices	Anaerobic Decomposition in Connected Wetlands

Once a probable stressor(s) was identified, a conceptual model was developed to describe the causal pathways linking pollutant sources to the probable stressors and mechanisms of impairment. The pathways in the conceptual model were then evaluated to determine if the existing data support those mechanisms for producing the impairment.

2.0 BIOLOGICAL, PHYSICAL, AND CHEMICAL DATA

For the stressor identification analysis, JMU used biological, physical, and chemical data from 49 VDEQ monitoring stations within the six project watersheds (Table 3). Water quality data was collected from all of these stations, and benthic data was collected from 14 of the stations. These VDEQ stations have been monitored for various parameters, lengths of time, and purposes. Table 3 shows the number of samples and the period of time over which individual stations were monitored. All data collected since 2000 was used in the stressor identification analysis.

For benthic monitoring stations, data include the taxonomic identification (family or genus level) and counts of the collected benthic macroinvertebrates, eight calculated benthic metrics, stream condition index scores (SCI), and visual habitat assessment scores. For water quality monitoring stations, data include results for various physical and chemical parameters. Across all of the stations and sampling dates, 360 different water quality parameters were measured. In total, more than 130,000 individual data points were compiled and incorporated into the stressor identification analysis.

In addition to sampling locations within the James River Tributaries Project area, unimpaired benthic and water quality monitoring stations located outside of the project area, in Powhatan County, were used as references for comparison. Data from two closely located stations on Jones Creek (station 2-JOH004.04 and 2-JOH004.23) were combined to represent a healthy benthic and water quality reference condition.

Table 3. Benthic and water quality data used in the stressor analysis.

Watershed	Stream	Station	Benthic Sampling		Water Quality Sampling	
			Monitoring Period	Samples Collected	Monitoring Period	Samples Collected
Bailey Creek	Bailey Creek	2-BLY003.42			2000-2020	43
		2-BLY005.73	2010-2019	4	2006-2020	42
	Southerly Run	2-SOU000.77			2012	12
Nuttree Branch	Nuttree Branch	2-NUT000.62	2010-2019	3	2010-2020	31
		2-NUT002.22			2008-2014	27
Oldtown Creek	Oldtown Creek	2-OTC001.54	2007-2019	6	2001-2020	44
		2-OTC005.38	2015-2019	3	2008-2020	31
Proctors Creek	Proctors Creek	2-PCT002.46	2007-2019	6	2005-2020	73
	Great Branch	2-GTB000.46			2014	10
		2-GTB000.65			2009-2015	13
	Redwater Creek	2-RDW000.50			2007-2009	13
Rohoic Creek	Rohoic Creek	2-RHC000.58	2010-2019	3	2003-2020	30
		2-RHC002.23			2009-2010	10
	Cattail Run	2-CLC000.62			2009-2010	10
Swift Creek	Swift Creek	2-SFT004.80			2007	3
		2-SFT004.92			2003-2012	48
		2-SFT005.57			2013-2020	11
		2-SFT006.10			2005-2013	108
		2-SFT006.88			2007-2008	24
		2-SFT012.84	2014	2	2003-2014	25
		2-SFT019.02	2008-2009	4	2008-2009	10
		2-SFT019.15	2010-2019	3	2000-2020	72
		2-SFT022.14			2003-2008	63
		2-SFT025.32	2008-2019	5	2007-2020	31
		2-SFT027.38			2007	12

		2-SFT030.65			2007	12
		2-SFT031.08			2001-2018	245
		2-SFT033.42			2001-2018	178
		2-SFT034.38			2001-2018	188
		2-SFT036.00			2000-2005	35
		2-SFT037.95			2009-2010	9
	Blackman Creek	2-BMC000.79			2001-2003	13
	Church Branch	2-CUR001.58			2008-2014	28
	Dry Creek	2-DYC000.19			2001-2018	206
	Franks Branch	2-FNK001.12			2001-2018	49
	Horsepen Creek	2-HEP001.27	2002	2	2002	2
	Licking Creek	2-LIA000.50	2008	1	2007-2008	25
	Long Swamp	2-LNS000.69			2007-2014	24
	Otterdale Branch	2DOTD002.52	2011	2	2011	2
	Reedy Branch	2-REY000.54			2007	12
	Second Branch	2-SEC004.81			2013	12
		2-SEC008.84			2008-2014	28
	Spring Run	2-SNC000.58			2007	12
		2-SNC001.92			2002-2003	15
	Third Branch	2DTRO001.88	2011	2	2011	2
		2-TRO002.23			2007	12
	Timsbury Creek	2-TBY001.54			2008-2014	28
	Unnamed Tributary to Swift Creek	2-XZG000.65			2007	12
Reference	Jones Creek	2-JOH004.04/4.23	2005-2019	6	2005-2020	29

2.1. Benthic Assessments

From 2002 to 2019, VDEQ conducted benthic assessments at 14 stations within the James River Tributaries Project area. Table 4 and Figure 3 show the average SCI scores for each station. All benthic scores within the Bailey Creek, Nuttree Branch, Oldtown Creek, Proctors Creek, and Rohoic Creek watersheds were below the impairment threshold score of 60 and ranged from 32.0 to 52.6. Within the Swift Creek watershed, the most downstream station (2-SFT012.84) was unimpaired with an SCI score of 71.9. All stations on Swift Creek upstream from this point showed impairment. Several tributaries to Swift Creek also were assessed. Third Branch was unimpaired, with a score of 67.2. Additionally, Licking Creek and Otterdale Branch had SCI scores below 60 but were assessed as “Insufficient Information” because of the low number of benthic samples.

Table 4. Benthic scores in the James River Tributaries Project area.

Watershed	Stream	Station	Years Sampled	Samples Collected	SCI Average	Assessment
Bailey Creek	Bailey Creek	2-BLY005.73	2010-2019	4	32.0	Impaired
Nuttree Branch	Nuttree Branch	2-NUT000.62	2010-2019	3	51.4	Impaired
Oldtown Creek	Oldtown Creek	2-OTC001.54	2007-2019	6	49.7	Impaired
		2-OTC005.38	2015-2019	3	50.8	Impaired
Proctors Creek	Proctors Creek	2-PCT002.46	2007-2019	6	51.0	Impaired
Rohoic Creek	Rohoic Creek	2-RHC000.58	2010-2019	3	48.8	Impaired
Swift Creek	Swift Creek	2-SFT012.84	2014	2	71.9	Unimpaired
		2-SFT019.02	2008-2009	4	48.0	Impaired
		2-SFT019.15	2010-2019	3	43.0	Impaired
		2-SFT025.32	2008-2019	5	44.7	Impaired
	Horsepen Creek	2-HEP001.27	2002	2	47.9	Impaired
	Licking Creek	2-LIA000.50	2008	1	56.4	Insufficient Information
	Otterdale Branch	2DOTD002.52	2011	2	57.1	Insufficient Information
	Third Branch	2DTRO001.88	2011	2	67.2	Unimpaired
Reference	Jones Creek	2-JOH004.04/4.23	2005-2019	6	60.7	Unimpaired

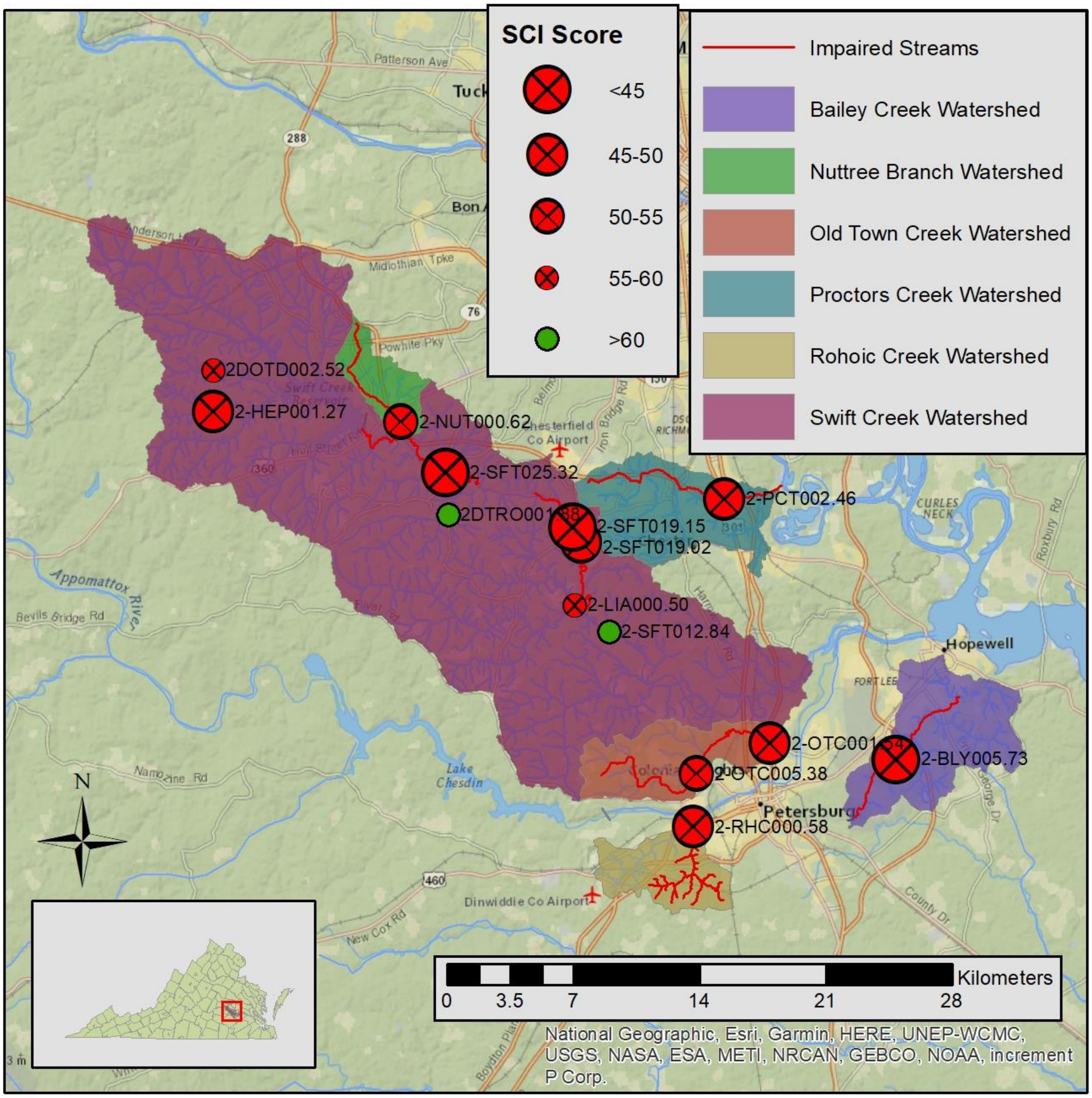

Figure 3. Benthic scores at monitoring stations within the James River Tributaries Project area.

2.1.1. Temporal and Seasonal Trends in Benthic Data

Figure 4 and Figure 5 show the temporal and seasonal trends in benthic data from the James River Tributaries Project streams.

- Bailey Creek – In Bailey Creek, SCI scores averaged 32.0 and ranged from 23.9 to 41.7. This site exhibited the most severe impairment of all James River Tributaries Project streams. Benthic samples collected in 2011 and 2019 showed no general overall trend of increasing or decreasing SCI scores. Scores in 2011 averaged 31.2, and scores in 2019 averaged 32.8. While there is no overall temporal trend in Bailey Creek SCI scores, there appears to be a strong seasonal trend. In both years, SCI scores were lower in the spring (averaging 25.0) than in the fall (averaging 39.0). This represents a 56% increase in SCI scores from spring to fall. While this difference was not statistically significantly different due to the low sample number, it might point to stressors that are related to spring high flow (such as nutrients or sediment) or to wintertime sources (such as deicing salt applications in highly-impervious watersheds). Lower springtime scores could also be due to changing habitat or food availability, such as leaf packs that are prevalent in the fall but scarce in the spring.

- <u>Nuttree Branch</u> – Benthic SCI scores in Nuttree Branch averaged 51.4 and ranged from 44.6 to 57.3. The most recent SCI score of 44.6 in 2019 was substantially lower than scores in 2010 (averaging 54.9). This could point toward a decreasing trend over time, but, it is difficult to assess temporal trends with only three samples. SCI scores were relatively consistent from spring (52.4) to fall (50.9), so no seasonal trend was apparent.

- <u>Oldtown Creek</u> – Benthic samples were collected from two Oldtown Creek locations (2-OTC001.54 and 2-OTC005.38). SCI scores were relatively consistent between these two locations, averaging 49.7 at 2-OTC001.54 and 50.8 at 2-OTC005.38. Scores ranged from a low of 32.5 in 2007 to a high of 63.6 in 2015. This fall 2015 sampling was the only occasion that Oldtown Creek showed benthic health above the impairment threshold. Despite the large range in SCI scores, there is no apparent temporal trend in Oldtown Creek benthic scores. There is also no apparent seasonal trend with spring SCI scores averaging 48.1 and fall scores averaging only slightly higher at 52.5.

- <u>Proctors Creek</u> – In Proctors Creek, SCI scores averaged 51.0 and ranged from 38.7 to 65.4. The fall 2007 score (64.3) and the fall 2019 score (65.4) were above the impairment threshold, but all other scores were below 60. Benthic samples collected from 2007 to 2011 showed no general overall temporal trend but the one 2019 sample was much higher. This could potentially indicate recent improvement. Proctors Creek benthic scores showed a strong seasonal trend. Spring SCI scores averaged 40.6, while fall scores averaged 61.5, above the impairment threshold. This represents a 51% increase in SCI scores from spring to fall, and it demonstrates that benthic conditions in the fall may be unimpaired or only marginally impaired. While the observed seasonal difference was not statistically significantly different due to the low sample number, it might point to stressors that are related to spring high flow (such as nutrients or sediment), wintertime sources (such as deicing salt applications in highly-impervious watersheds), or changing habitat or food availability.

- Rohoic Creek – Benthic SCI scores in Rohoic Creek averaged 48.8 and ranged from 29.6 in spring 2010 to 67.2 in fall 2019. The most recent SCI score of 67.2 in fall 2019 was above the impairment threshold and substantially higher than scores in 2010 (averaging 39.6). This could point toward an increasing trend over time, but, it is difficult to assess temporal trends with only three samples. SCI scores also varied substantially by season with the only spring score at 29.6 and the average of fall scores at 58.4, however, it is difficult to assess seasonal trends with only three samples.
- Swift Creek – Benthic samples were collected from four Swift Creek locations (2-SFT012.84, 2-SFT019.01, 2-SFT019.15, and 2-SFT025.32). At the most downstream location (2-SFT012.84), benthic health is unimpaired and SCI scores average 71.9. At all other upstream locations, benthic health is impaired and SCI scores average 45.4. Among the three impaired stations, SCI scores are relatively consistent, with averages between 43.0 and 48.0. SCI scores are also relatively consistent over time at the three impaired stations, indicating no temporal trend. SCI scores do, however, exhibit a strong and statistically significant ($p = 0.03$) seasonal trend. Spring SCI scores at the three impaired stations averaged 37.4, while fall scores averaged 51.1. This represents a 37% increase in SCI scores from spring to fall, and it may point to stressors that are related to spring high flow (such as nutrients or sediment), wintertime sources (such as deicing salt applications in highly-impervious watersheds), or changing habitat or food availability.

In summary, no conclusive temporal trends were observed in benthic data. Benthic conditions may be increasing over time in Rohoic Creek and decreasing over time in Nuttree Branch, but there is not enough data from these two stations to confirm this observation. Four streams (Bailey Creek, Proctors Creek, Rohoic Creek, and Swift Creek) showed strong seasonal trends with benthic SCI scores lower in the spring and higher in the fall. This was statistically significant for the case of Swift Creek, which had the largest data set. The seasonal difference was even larger in Proctors Creek and Bailey Creek, but this difference was not statistically significant in those smaller data sets. The lower spring benthic scores in these three streams may point to stressors that are related to spring high flow (such as nutrients or sediment), wintertime sources (such as deicing salt applications in highly-impervious watersheds), or changing habitat or food availability.

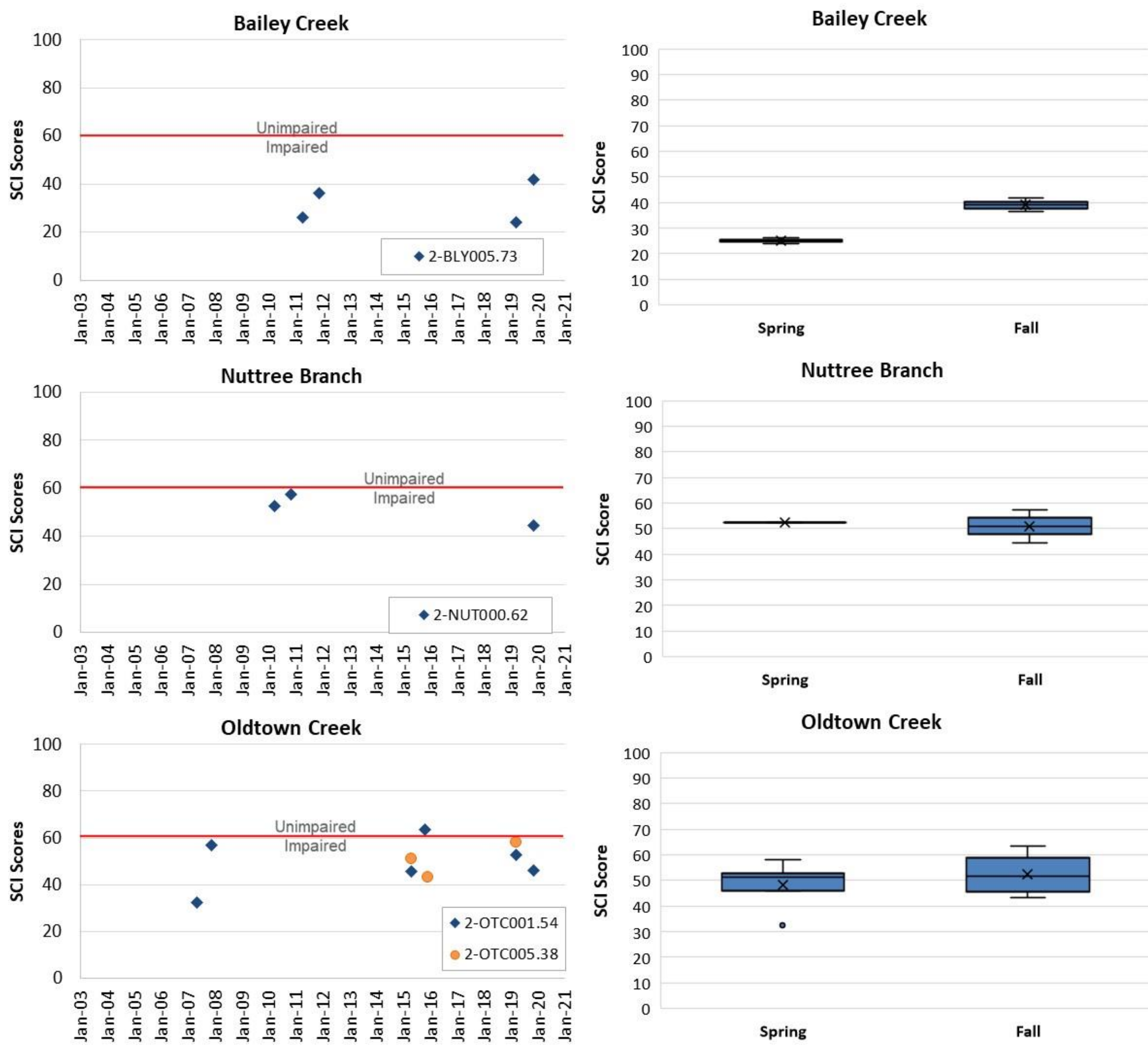

Figure 4. Temporal trends in benthic data for Bailey Creek, Nuttree Branch, and Oldtown Creek.

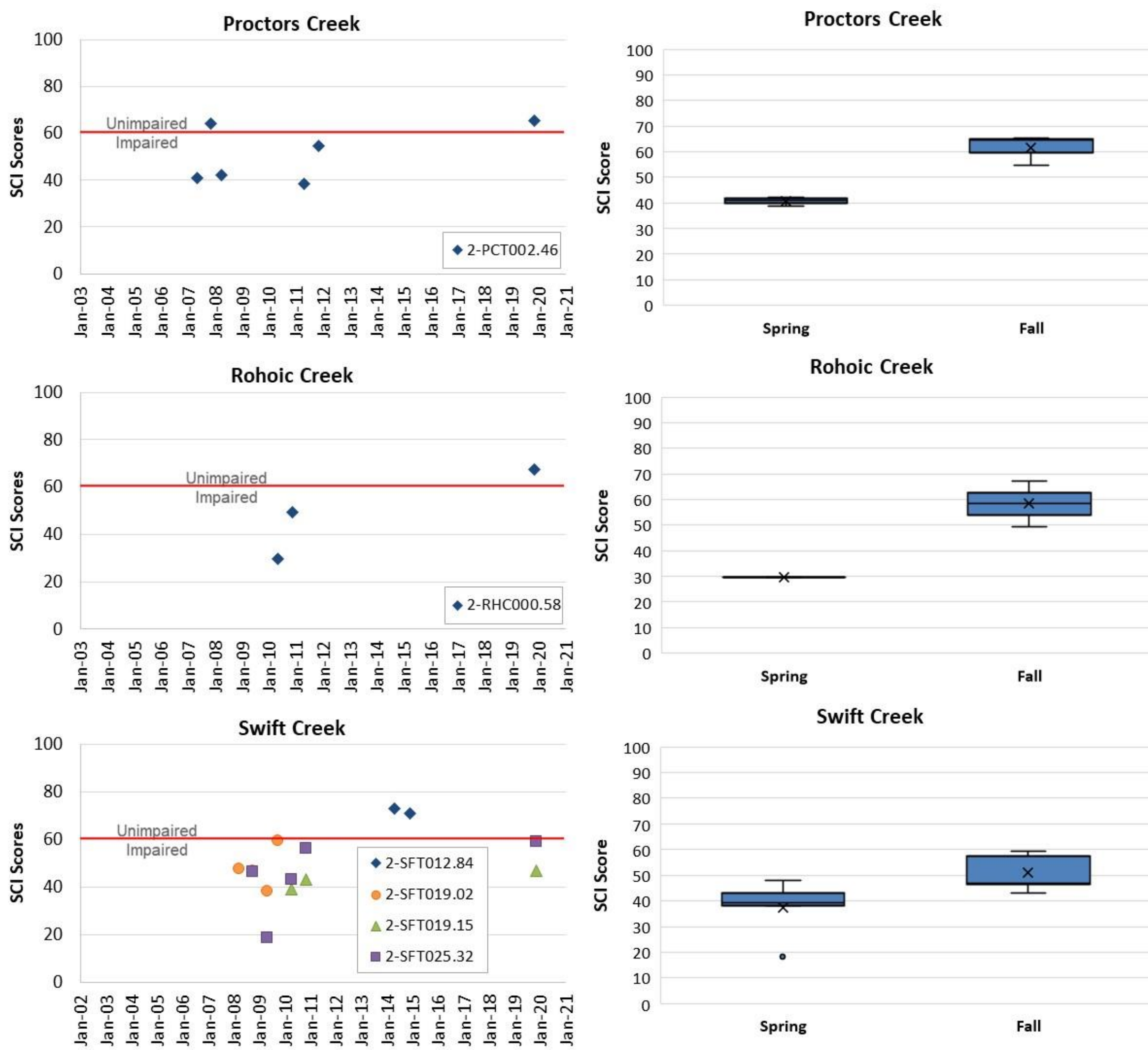

Figure 5. Temporal trends in benthic data for Proctors Creek, Rohoic Creek, and Swift Creek.

2.1.2. Analysis of Benthic Metrics

For stations where VDEQ data were available, the individual metrics that comprise the SCI were evaluated in comparison to Jones Creek, a benthic reference stream (Figure 6). Average metric scores from each station were compared to the reference using a t-test with unequal variances (alpha = 0.05).

- <u>Bailey Creek</u> – In Bailey Creek, all metrics except for % scrapers and % 2 dominant were significantly lower ($p<0.05$) than the reference. Scores for EPT richness, %

Ephemeroptera, and % PT-Hydro (% Plecoptera and Trichoptera minus *Hydropsychidae*) were extremely low (27, 5.6, and 10, respectively). A maximum of four EPT taxa (including *Hydropsychidae*) were identified in any of the benthic samples from Bailey Creek. This indicates that water quality or habitat conditions are severely limiting the presence of sensitive EPT taxa.

- <u>Nuttree Branch</u> – In Nuttree Branch, metric scores for species richness, EPT richness, and % PT-Hydro were significantly lower ($p<0.05$) than the reference condition. Other metrics were either similar (% 2 dominant) or slightly greater than the reference site (% *Ephemeroptera*, % scrapers, % *Chironomidae*, and MFBI). The total number of taxa at the site ranged from 8-14, and the number of EPT taxa ranged from 3-5. This represents a relatively low diversity of sensitive taxa, but the abundance of sensitive taxa was high. The most abundant macroinvertebrate in all Nuttree Branch samples was the mayfly (Ephemeroptera) genus *Caenis*. *Caenis* prefer slow moving water with an abundance of silt and loose sediment, so high abundance of this genus may indicate sediment enrichment as a potential stressor.

- <u>Oldtown Creek</u> – In Oldtown Creek, metric scores for species richness, EPT richness, % Ephemeroptera, and % PT-Hydro were significantly lower ($p<0.05$) than the reference condition. Other metrics were either similar (% 2 dominant and MFBI) or slightly greater than the reference site (% scrapers and % *Chironomidae*). Species and EPT richness were somewhat variable, with the total number of taxa ranging from 9-23 and the number of EPT taxa ranging from 2-7. This indicates that conditions in Oldtown Creek can support a healthy and diverse benthic community, but that conditions vary considerably over time. The low % Ephemeroptera may also point to low pH and acidity. Courtney and Clements (1998) found that Ephemeroptera were the most sensitive order to low pH conditions and that abundance significantly dropped at treatments with pH <5.5.

- <u>Proctors Creek</u> – In Proctors Creek, metric scores for species richness, EPT richness, and % Ephemeroptera were significantly lower ($p<0.05$) than the reference condition. Species richness was low, but consistent, with the total number of taxa ranging only from 11-13. EPT richness was also low, but relatively consistent, with the number of EPT taxa ranging from 4-7. For the remaining metrics, scores were either similar (% PT-Hydro, %

2 dominant, and MFBI) or slightly greater than the reference site (% scrapers and % *Chironomidae*). Conditions in Proctors Creek appear to be limiting the diversity of more sensitive species but not necessarily encouraging the dominance of tolerant species. The low % Ephemeroptera may also point to low pH and acidity. Courtney and Clements (1998) found that Ephemeroptera were the most sensitive order to low pH conditions and that abundance significantly dropped at treatments with pH <5.5.

- Rohoic Creek – In Rohoic Creek, metric scores for species richness, EPT richness, and % scrapers were significantly lower ($p<0.05$) than the reference condition. Other metrics were either similar (% *Ephemeroptera* and % 2 dominant) or slightly greater than the reference site (% PT-Hydro, % *Chironomidae*, and MFBI). The total number of taxa ranged from 8-15, and the number of EPT taxa ranged from 4-7. Scrapers were almost non-existent in Rohoic Creek. No scrapers were found in the 4/27/10 benthic sample, and scrapers only represented 6% of the population in the other two benthic samples. The sample with the lowest SCI score (29.6) also occurred on 4/27/10 when no scrapers were present. The absence or limited number of scrapers could be indicative of sediment as a stressor. With excess sediment, rock substrates become embedded and available habitat for periphyton growth is limited. The decrease in periphyton limits scraper populations.
- Swift Creek – In Swift Creek, metric scores for EPT richness, % *Chironomidae*, % 2 dominant, and % MFBI were significantly lower ($p<0.05$) than the reference condition. Other metrics were either similar (species richness, % *Ephemeroptera*, % PT-Hydro) or slightly greater than the reference site (% scrapers). This pattern is somewhat different than the pattern observed in other James River Tributaries Project streams. Species richness was relatively high (averaging 15 total taxa), but the community was dominated by *Chironomidae*. *Chironomidae* is a family of sediment-loving midge larvae, so their abundance indicates excess sediment conditions. The Modified Family Biotic Index (MFBI) is an index developed based on tolerance to organic enrichment, so low scores for this metric indicate the possibility of nutrient or organic enrichment and resulting low dissolved oxygen conditions. Since Swift Creek is larger than the other streams in this project and is dammed to form two large impoundments, it is not unexpected that the pattern of benthic community metrics in Swift Creek is different than in the other project

streams. The differing patterns may indicate different stressors or may simply reflect differing environmental conditions.

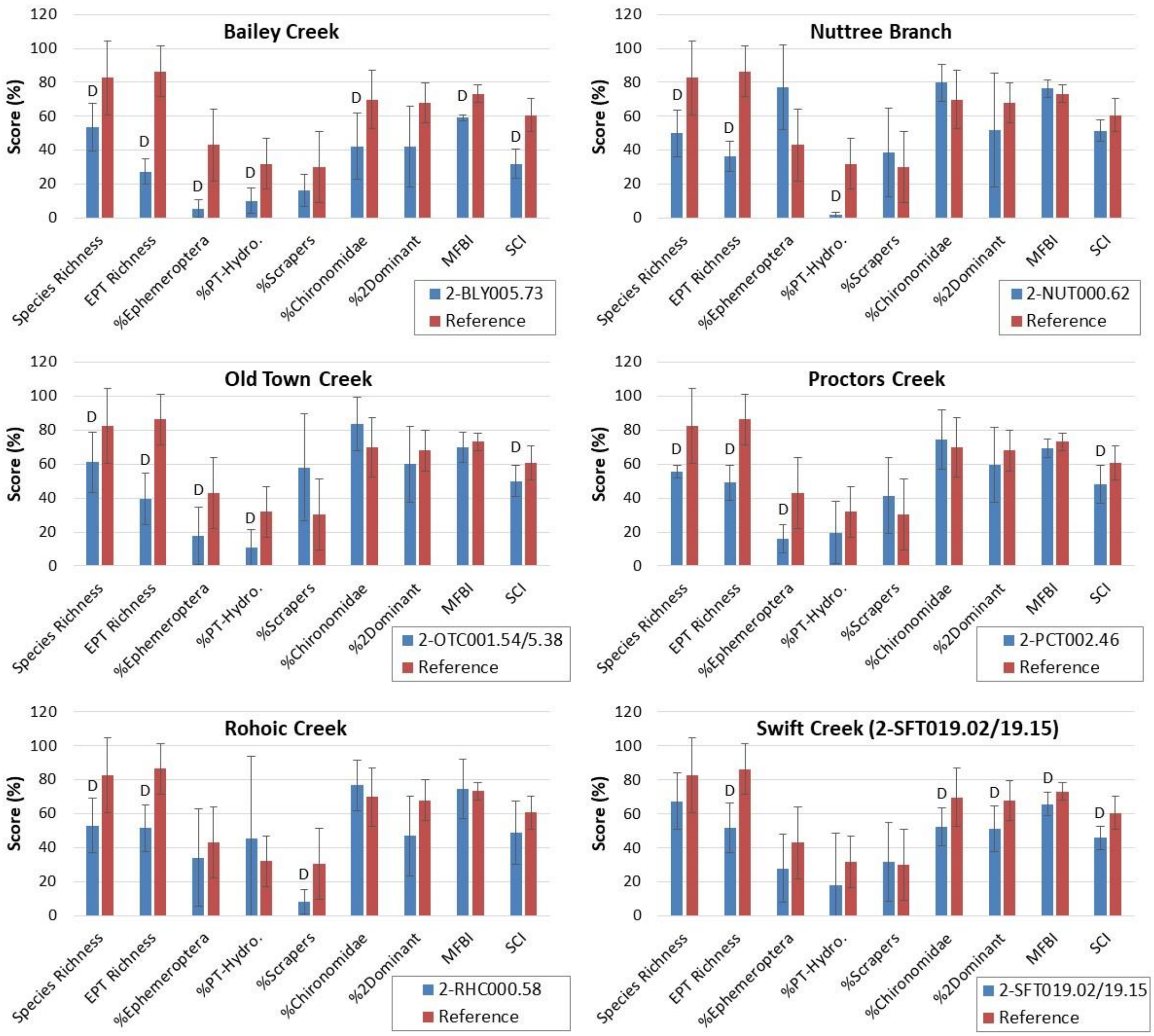

Figure 6. Individual metric scores comprising the stream condition index (SCI) in James River Tributaries Project streams. "D" indicates that the metric was significantly different (alpha = 0.05) from the benthic reference.

2.1.3. Analysis of Community Composition

The taxonomic composition of the benthic communities was analyzed to identify shifts in composition at impaired stations that might provide clues to sources or mechanisms of impairment.

Figure 7 compares the taxonomic composition in James River Tributaries Project streams to a reference stream. In the reference stream, taxonomic composition is relatively balanced. Sensitive taxonomic categories, such as Ephemeroptera, Trichoptera, and Plecoptera (EPT), each represent at least 6% of the community, and no one category represents more than 32% of the community. In impaired streams, the community composition is generally shifted to include greater dominance by one or two taxonomic categories with less diversity and balance.

- <u>Bailey Creek</u> – Taxonomic composition in Bailey Creek was significantly altered from that of the reference stream. Sensitive EPT taxa represented only 7% of the community in Bailey Creek, compared to 45% in the reference. Dipteran taxa increased from 32% in the reference to 60% of the community in Bailey Creek. Another significant shift in community composition was an increase in Oligochaeta/Tubificida taxa (aquatic worms), which were virtually non-existent in the reference, but comprised 12% of the Bailey Creek benthic community. These changes reflect a general shift from the more sensitive EPT taxa to more pollution tolerant dipteran and oligochaete taxa. The Diptera present in Bailey Creek were predominantly midges (*Chironomidae*), which could be indicative of nutrient or sediment enrichment. Lawrence and Gressens (2011) showed that Chironomid abundance correlated with increased nutrient enrichment in urban and rural streams. Bjornn *et al.* (1977) demonstrated in artificial mesocosm experiments that increases in fine sediment significantly reduced EPT taxa but were tolerated by Chironomid taxa. Similarly, the Oligochaeta/Tubificida taxa thrive in fine sediment rich in organic matter (Voshell, 2002). These shifts in community composition indicate that fine sediment and deposited organic matter may be stressors in Bailey Creek.
- <u>Nuttree Branch</u> – The taxonomic composition of Nuttree Branch was somewhat unique among the James River Tributaries Project streams. While the presence of EPT taxa was relatively high (55%), Plectoptera and Trichoptera were nearly absent (<1%) and one Ephemeroptera genus (*Caenis*) represented 81% of the EPT abundance. *Caenis* thrive in ponds and lakes or in silty or sandy depositional zones of streams. According to Voshell (2002), this group is an exception to the rule about Ephemeroptera being indicators of good water quality. “They can be found in degraded conditions – especially those characterized by low dissolved oxygen, sedimentation, and nutrient enrichment” (Voshell, 2002). The

predominance of *Caenis* in Nuttree Branch indicates that sedimentation and nutrient enrichment may be stressors in Nuttree Branch.

- Oldtown Creek – The taxonomic composition in Oldtown Creek at station 2-OTC001.54 is very balanced (even more than the reference); however, Plecoptera and Trichoptera were virtually absent (<1%). At station 2-OTC005.38, the community was dominated by Diptera (41%) and Coleoptera (37%). The predominant dipteran genus was *Prosimulium*, a member of the *Simullidae* or black fly family, and the predominant Coleoptera was *Stenelmis*, the riffle beetle. Both black fly larvae and the riffle beetle generally inhabit fast flowing water. Neither are particularly pollution tolerant, however due to the filter feeding nature of black fly larvae, their presence in high numbers can be an indicator of moderate organic or nutrient enrichment (Voshell, 2002).

- Proctors Creek – Proctors Creek exhibited a moderate decrease in EPT taxa from 45% in the reference to 19% in Proctors Creek. Diptera increased from 32% in the reference to 49% in Proctors Creek. The Diptera present in Proctors Creek were mostly midges (*Chironomidae*) and black flies (*Simuliidae*), which could be indicative of nutrient or sediment enrichment. Lawrence and Gressens (2011) showed that Chironomid abundance correlated with increased nutrient enrichment in urban and rural streams. Bjornn *et al.* (1977) demonstrated in artificial mesocosm experiments that increases in fine sediment significantly reduced EPT taxa but were tolerated by Chironomid and Simuliid taxa. This shift in community composition could indicate that sedimentation and nutrient enrichment may be stressors in Proctors Creek.

- Rohoic Creek – Rohoic Creek exhibited only a slight decrease in EPT taxa, from 45% in the reference to 39% in Rohoic Creek. Like Proctors Creek, Diptera taxa were increased in Rohoic Creek (46%), and those Diptera taxa were primarily represented by midges (*Chiromonidae*) and black fly larvae (*Simullidae*). This shift in community composition could indicate that sedimentation and nutrient enrichment may be stressors in Rohoic Creek.

- Swift Creek – Benthic community composition was assessed at four locations along Swift Creek (Figure 8). At the unimpaired station (2-SFT012.84), taxonomic composition was very well-balanced, with EPT taxa comprising 15-21% each and no taxa accounting for more than 25% of the community. At the impaired stations, the community was much less balanced. EPT taxa decreased by 28-36% at impaired stations, Oligochaeta/Tubificida increased by 7-19%, and Diptera taxa increased by 22-32%. At impaired Swift Creek stations, the increase in Diptera taxa was almost exclusively attributed to midges (*Chironomidae*) and not black fly larvae (*Simullidae*) as in other streams. This pattern, along with the increase in aquatic worms indicates that sediment enrichment and not nutrient enrichment is a likely stressor.

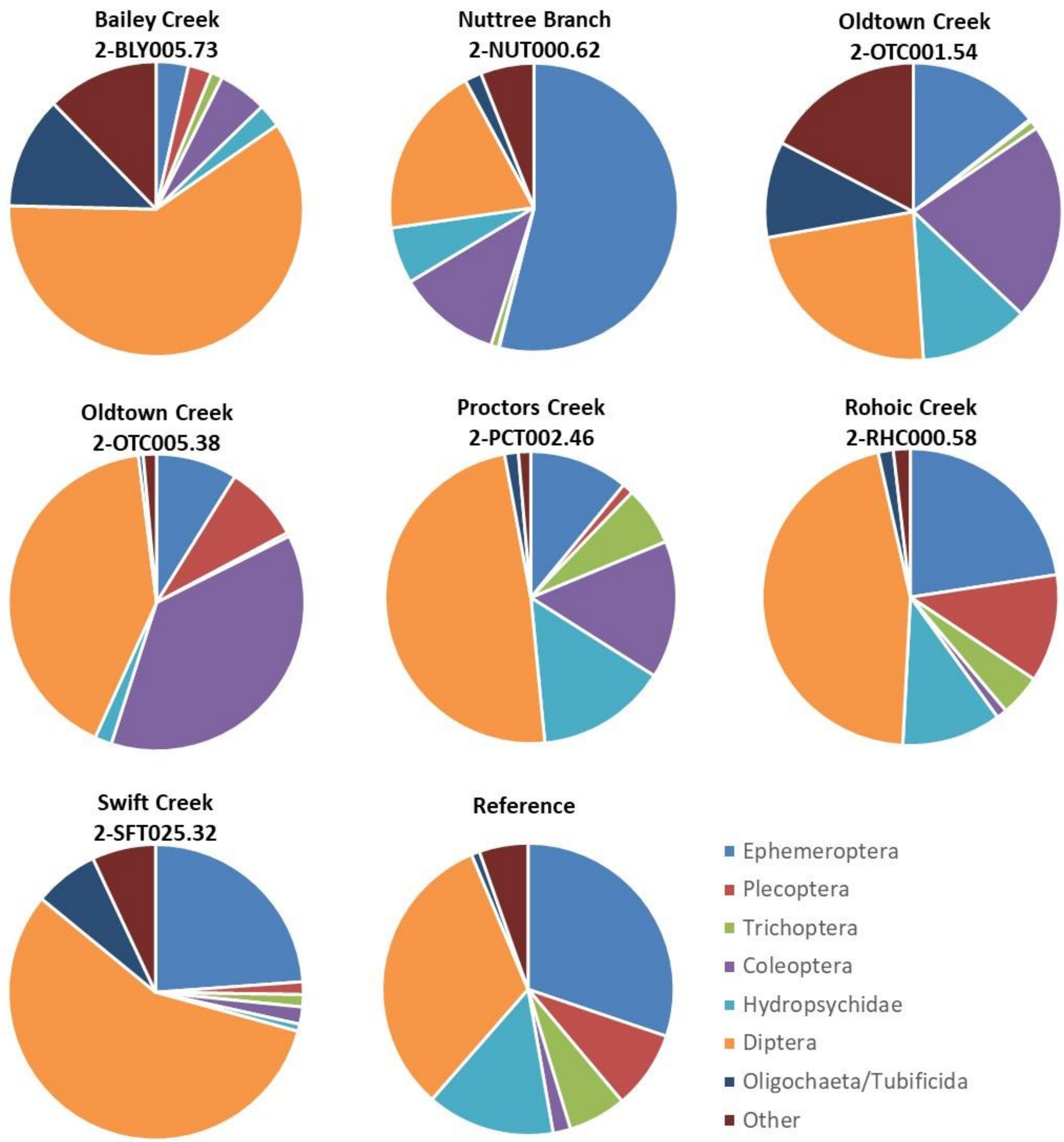

Figure 7. Taxonomic composition of James River Tributaries Project streams compared to a reference.

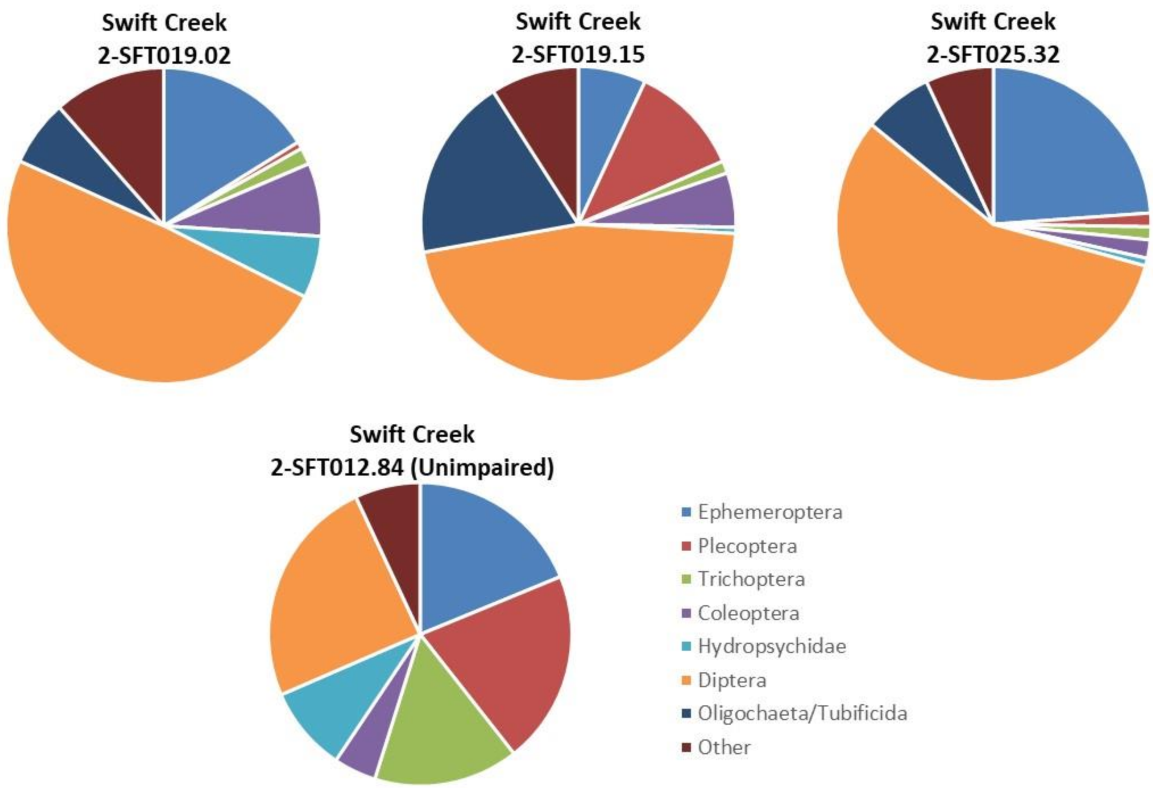

Figure 8. Taxonomic composition of impaired and unimpaired Swift Creek stations.

2.1.4. Biological Condition Gradient Analysis

In 2019, Tetra Tech worked with mid-Atlantic region states (including Virginia) to develop a conceptual model of environmental condition called the Biological Condition Gradient (BCG). The BCG model describes environmental conditions by analyzing patterns of pollution tolerance among fish and macroinvertebrates present (Tetra Tech, 2019). The model defined six attributes related to pollution tolerance and scored these attributes across 560 macroinvertebrate taxa for 10 specific stressors (Table 5). Attributes were scored for each taxa and stressor combination based on statistical analysis of regional data and expert consensus. The result is a database that can be useful for stressor analysis.

Using attribute data from the BCG model, taxa present at each of the impaired James River Tributaries Project streams were assigned attribute scores for each stressor. The average scores and the scores for predominant species were evaluated for each stressor to identify potential stressors that might be indicative of the pattern of organism tolerance observed. Table 6 shows the BCG scores for the three most prevalent taxa at each of the impaired monitoring stations. Attribute scores of 5 indicate tolerant taxa that would be expected to increase in number when the respective stressor is present. Some taxa, like *Chironomidae*, are relatively tolerant to a wide range of stressor and don't show much differentiation with respect to stressor identification. Others, like *Caenis*, show better differentiation and can be indicators of specific stressors.

Table 5. Biological condition gradient attributes and stressors evaluated.

Attribute	Explanation	Stressors Evaluated
I	Historically documented, sensitive, long-lived or regionally endemic taxa	Dissolved oxygen Acidity
II	Highly sensitive taxa	Alkalinity
III	Intermediate sensitive taxa	Specific Conductivity
IV	Intermediate tolerant taxa	Chloride
V	Tolerant taxa	Sulfate
VI	Non-native taxa	Total Nitrogen and Phosphorus
		Total Habitat Relative Bed Stability %Imperviousness

In Bailey Creek, *Oligochaeta* are indicative of a wide range of potential stressors, but the dominant presence of *Argia* might indicate increased imperviousness as a likely stressor in the watershed. In Nuttree Branch, the dominant presence of *Caenis* points to excess sediment as a stressor. In Oldtown Creek, *Oligochaeta* points to a wide range of potential stressors, and *Stenelmis* potentially implicates conductivity, habitat, and percent imperviousness. No strong indicators were present in Proctors Creek. In Rohoic Creek, *Simulium* implicates nutrient enrichment and sulfate as potential stressors, and *Caenis* implicates sediment enrichment. In Swift Creek, *Oligochaeta* indicates a wide range of potential stressors, *Cheumatopsyche* implicates conductivity, nutrients, and percent imperviousness, while *Caenis* points to sediment enrichment.

In addition to analyzing the BCG attribute scores for the top three dominant taxa in each impaired stream, BCG attribute scores of all present taxa were averaged to calculate mean scores for each stressor in each stream. Those scores were then ranked to identify the stressors with the highest three scores (Table 7). These represent the stressors that have the greatest likelihood of impact on each stream based on the taxa present and BCG attribute scores for those taxa. For all impaired streams, the top three stressors were some combination of sediment enrichment (through habitat, RBS or % imperviousness measures) and nutrients.

Table 6. Biological condition gradient scores for three most prevalent taxa at each impaired station.

Stream	Station	Predominant Taxa	General	Diss. Oxy.	Acidity	Alkalinity	Spec. Cond.	Chloride	Sulfate	TN/TP	Total Habitat	RBS	% Imp.
Bailey Creek	2-BLY005.73	Chironimidae	4	4	4	4	4	4	4	4	4	4	4
		Oligochaeta	5	4	4	3	5	4	4	5	5	5	5
		Argia	4	4	3	4	4	4	4	4	4	4	5
Nuttree Branch	2-NUT000.62	Caenis	4	4	3	4	4	4	4	4	4	5	5
		Chironomidae (A)	4	4	4	4	4	4	4	4	4	4	4
		Maccaffertium	4	4	4	4	3	3	3	4	4	4	4
Oldtown Creek	2-OTC001.54	Stenelmis	4	4	4	4	5	4	4	4	5	4	5
		Chironomidae (A)	4	4	4	4	4	4	4	4	4	4	4
		Oligochaeta	5	4	4	3	5	4	4	5	5	5	5
	2-OTC005.38	Stenelmis	4	4	4	4	5	4	4	4	5	4	5
		Prosimulium	3	4	4	4	3	4	4	3	3	4	2
		Maccaffertium	4	4	4	4	3	3	3	4	4	4	4
Proctors Creek	2-PCT002.46	Simuliidae	4	3	4	4	3	3	3	4	4	4	4
		Chironomidae (A)	4	4	4	4	4	4	4	4	4	4	4
		Hydropsychidae	4	3	3	4	4	3	4	4	4	4	4
Rohoic Creek	2-RHC000.58	Chironomidae (A)	4	4	4	4	4	4	4	4	4	4	4
		Simulium	4	4	4	4	4	3	5	5	4	4	4
		Caenis	4	4	3	4	4	4	4	4	4	5	5
Swift Creek	2-SFT019.02	Chironomidae (A)	4	4	4	4	4	4	4	4	4	4	4
		Maccaffertium	4	4	4	4	3	3	3	4	4	4	4
		Cheumatopsyche	5	4	3	4	5	4	4	5	4	4	5
	2-SFT019.15	Chironomidae (A)	4	4	4	4	4	4	4	4	4	4	4
		Taeniopteryx	4	3	3	4	3	3	4	4	4	4	3
		Oligochaeta	5	4	4	3	5	4	4	5	5	5	5
	2-SFT025.32	Chironomidae (A)	4	4	4	4	4	4	4	4	4	4	4
		Caenis	4	4	3	4	4	4	4	4	4	5	5
		Oligochaeta	5	4	4	3	5	4	4	5	5	5	5

Table 7. Rank of average biological condition gradient scores for each stressor in each impaired stream.

Stream	Station	Diss. Oxy.	Acidity	Alkalinity	Spec. Cond.	Chloride	Sulfate	TN/TP	Total Habitat	RBS	% Imp.
Bailey Creek	2-BLY005.73	6	8	10	5	9	7	2	3	1	4
Nuttree Branch	2-NUT000.62	6	9	10	5	8	6	2	4	3	1
Oldtown Creek	2-OTC001.54	6	8	10	5	8	7	1	3	2	4
	2-OTC005.38	7	8	10	6	9	5	1	3	2	4
Proctors Creek	2-PCT002.46	7	6	9	5	10	8	3	4	1	2
Rohoic Creek	2-RHC000.58	7	10	9	4	7	6	2	5	3	1
Swift Creek	2-SFT019.02	7	10	9	4	8	6	1	5	2	3
	2-SFT019.15	6	9	10	5	8	7	1	4	1	3
	2-SFT025.32	5	9	10	5	8	7	1	4	2	3

2.1.5. Analysis of Functional Feeding Groups

The composition of functional feeding groups comprising the benthic community was also analyzed to identify shifts in composition at impaired stations that might provide clues to sources or mechanisms of impairment. Figure 9 shows the composition of functional feeding groups within the James River Tributaries Project streams in comparison to a reference stream. Two distinct patterns emerged from this analysis. In Bailey Creek, Nuttree Branch, and Swift Creek, communities shifted to a higher percentage of collectors, while filterers, scrapers, and shredders decreased. Collectors increased by 22%, 22%, and 34% in Bailey Creek, Nuttree Branch, and Swift Creek, respectively. This shift in functional feeding group is indicative of increased deposited sediment and deposited organic material. As the amount of deposited organic matter increases, the niche of macroinvertebrates that collect their food from bottom deposits (collectors) expands. The shifts in functional feeding group observed in these three streams is not indicative of nutrient enrichment. If the supply of dissolved nutrients were in excess, algae growth would be spurred and the available food source for scrapers would increase (unless excess sediment smothered periphyton surfaces). If the supply of suspended particulate nutrients were in excess, filterers would increase as they take advantage of the increased flow of nutrients. In each of these streams, scraper and filterer composition decreased and accounted for less than 21% of the benthic community.

The pattern that was observed in Oldtown Creek, Proctors Creek, and Rohoic Creek was an increase in filterers and/or scrapers and a decrease in collectors and shredders (except for Rohoic Creek). Filterers increased by 21%, 21%, and 19% in Oldtown Creek, Proctors Creek, and Rohoic Creek, respectively. Scrapers increased by 27% in Oldtown Creek and 5% in Proctors Creek. This shift in functional feeding group points to an increase in nutrients and suspended organic matter. As nutrients increase, algae growth is spurred and provides an increased availability of food for scrapers. The increase in suspended nutrients and organic matter make more food available for filterers that can remove those free-flowing nutrients from the water column.

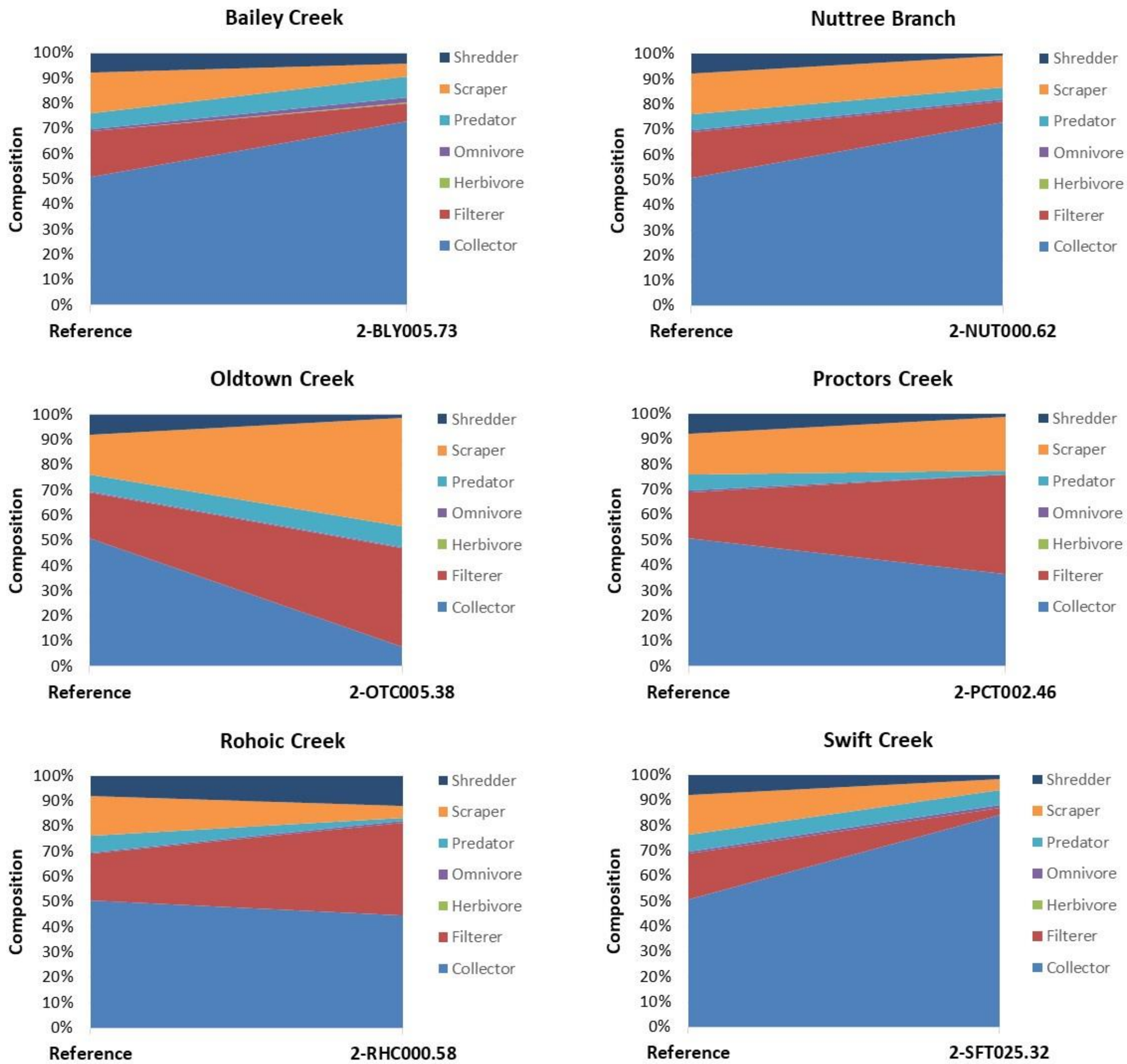

Figure 9. Functional feeding group composition in James River Tributaries Project streams compared to a reference.

2.2. Habitat Assessment

As part of the Rapid Bioassessment Protocol, a visual habitat assessment is performed at the time of each benthic sample collection. This assessment entails scoring each of a series of habitat components from 0 to 20. These habitat components include substrate, embeddedness (or pool substrate for low gradient streams), velocity (or pool variability for low gradient streams), sediment, flow, channel alteration, riffles (or sinuosity for low gradient streams), bank stability, bank vegetation, and riparian vegetation. The individual scores for each of these measures are then added for a total habitat score. Figure 10 compares the total habitat scores in the James River Tributaries Project streams with those from a reference stream. While total habitat scores averaged 137 at the reference site, scores at impaired stations ranged from 116 in Bailey Creek to 148 in Proctors Creek. Total habitat scores were statistically lower ($p<0.05$ in a one-tailed t-test with unequal variance) than the reference in Bailey Creek, Nuttree Branch, Oldtown Creek (at 2-OTC001.54), and Rohoic Creek.

Based on VDEQ's analysis of probabilistic monitoring data (VDEQ, 2017), the colors shown in Figure 10 represent the probability of habitat being a stressor on the aquatic community. Bailey Creek, Oldtown Creek, and Rohoic Creek fell in the medium probability category, while Nuttree Branch, Proctors Creek, and Swift Creek fell in the low probability category.

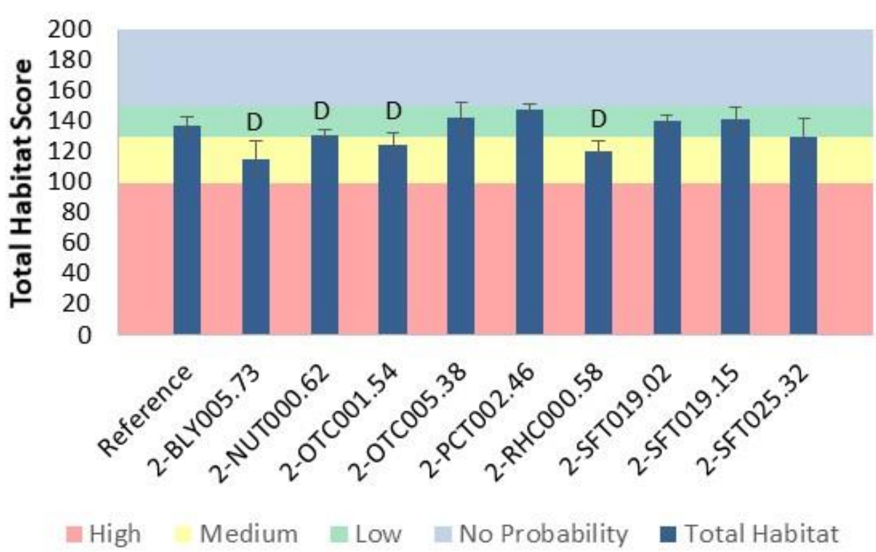

Figure 10. Total habitat scores for James River Tributaries Project streams. Streams with a "D" have statistically lower habitat scores than the reference site. Colors represent the probability that data within that range would be responsible for causing stress.

Individual habitat metrics are shown in Figure 11. At each location, several habitat metrics were significantly lower (on-tailed t-test with unequal variances, alpha = 0.05) than in the reference stream. In Bailey Creek, substrate, embeddedness/pool substrate, sediment, flow, and channel alteration were significantly lower than the reference. In Nuttree Branch, channel alteration and riparian vegetation were significantly lower than the reference. In Oldtown Creek, embeddedness/pool substrate, flow, channel alteration, and riparian vegetation were significantly lower than the reference. In Proctors Creek, only riparian vegetation was significantly lower than the reference. In Rohoic Creek, embeddedness/pool substrate, flow, channel alteration, and riparian vegetation were significantly lower than the reference. In Swift Creek, embeddedness/pool substrate, sediment, and flow were significantly lower than the reference. While a different combination of metrics were reduced across the different stations, all impaired stations had reductions in some habitat metric. In Bailey Creek, Oldtown Creek, Rohoic Creek, and Swift Creek, habitat metrics that indicate degraded instream conditions due to excess sediment (like embeddedness/pool substrate or sediment) were significantly reduced. This could indicate excess sediment as a stressor in these streams. In Nuttree Branch and Proctors Creek, only riparian vegetation and channel alteration metrics were significantly reduced. These indicators impact sediment loads and transport, but do not directly implicate excess sediment as a stressor.

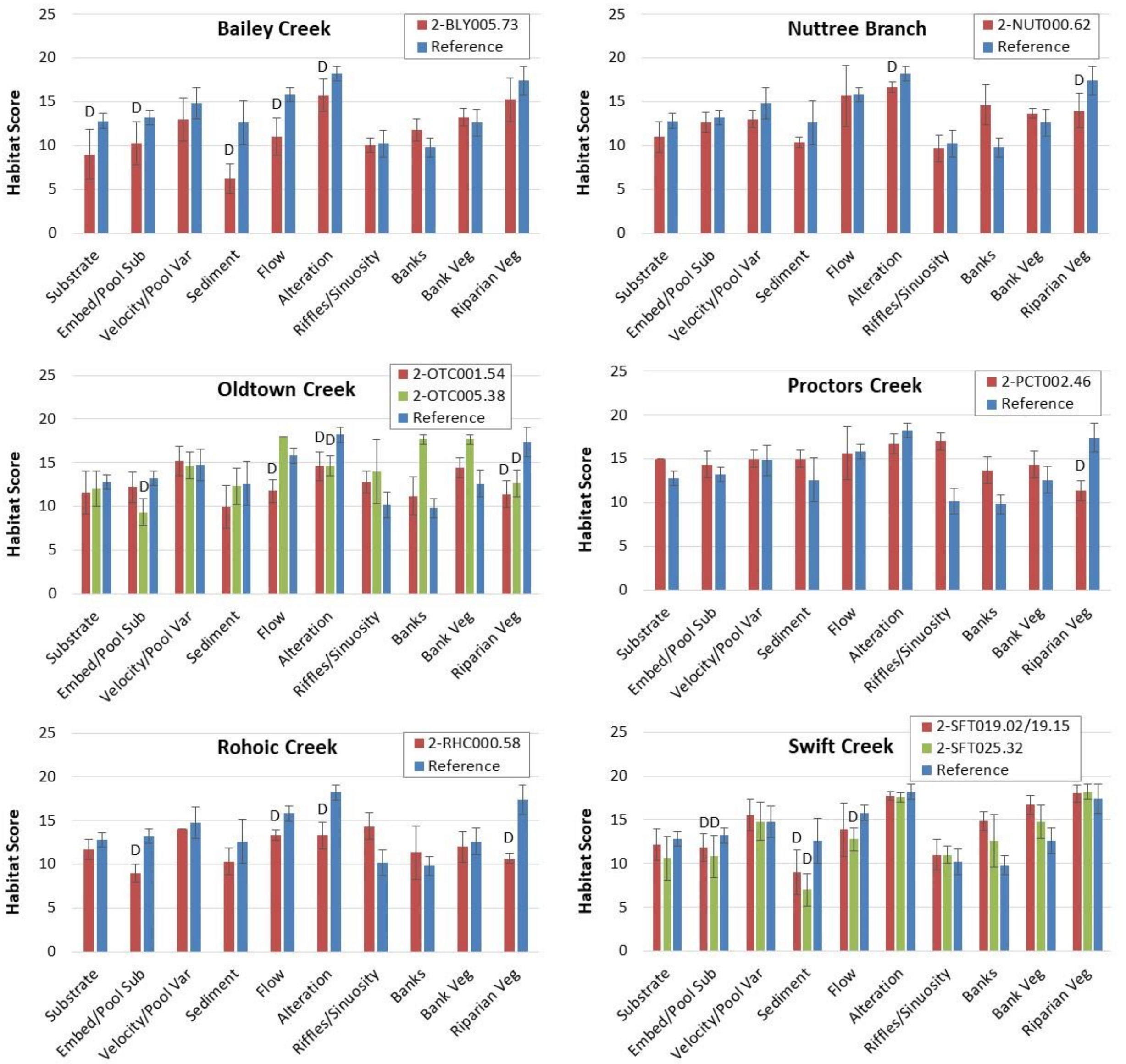

Figure 11. Habitat metric scores for the James River Tributaries Project streams. Metrics with a "D" are statistically lower than the reference site.

As a part of TMDL monitoring, VDEQ conducted a detailed physical habitat assessment of the impaired streams according to EPA methods for *Quantifying Physical Habitat in Wadeable Streams* (Kaufmann *et al*., 1999). This analysis involved the measurement of channel dimensions and substrate composition at numerous transects within a 150 to 800 m stream reach surrounding the benthic monitoring station. The outcome of this analysis is the calculation of a log relative bed stability index (LRBS). The LRBS is the ratio between the observed size distribution of in-stream sediments and the predicted sediment size distribution based on bankfull depth. LRBS values near zero indicate that the stream is stable. Large negative values indicate that the stream is unstable and depositing excess sediment. Large positive numbers, while less common, indicate that the stream is unstable and sediment starved. In an analysis of streams across the commonwealth, VDEQ has determined that LRBS scores between -1.0 and -1.5 have a medium probability of stressing aquatic life, and LRBS scores <-1.5 have a high probability of stressing aquatic life (VDEQ, 2017). LRBS scores that are too high can also stress benthic macroinvertebrates, and scores >0.5 are also in medium probability range for stress effects.

Table 8 shows the results of relative bed stability analysis in the James River Tributaries Project area. All of the impaired streams exhibited relatively sandy substrates with high embeddedness. Sand and fine sediment represented more than 50% of the bottom substrate in Bailey Creek, Nuttree Branch, Rohoic Creek, and Swift Creek. Embeddedness was above 50% in all of the streams and above 80% in Bailey Creek and Swift Creek. LRBS indices were in the medium probability range for stressor effects in Nuttree Branch, Oldtown Creek, Rohoic Creek, and Swift Creek. This could indicate the possibility of sediment stressor effects in these streams, however, it should be noted that the reference stream (Jones Creek) had a lower LRBS score than any of the impaired streams.

Table 8. Log relative bed stability index for James River Tributaries Project streams.

Stream	Station	Date	Slope	% Sand and Fines	Embeddedness (%)	Log Relative Bed Stability Index (LRBS)[1]
Bailey Creek	2-BLY005.73	3/11/2020	0.045	61.0	82.5	-0.40
Nuttree Branch	2-NUT000.62	11/1/2010	0.43	62.9	72.5	-1.11
		1/29/2020	0.58	54.3	68.2	-0.67
Oldtown Creek	2-OTC001.54	11/4/2015	0.33	43.8	54.7	-1.02
	2-OTC005.38	3/11/2020	0.47	32.4	74.7	-0.15
Proctors Creek	2-PCT002.45	1/29/2020	0.58	21.9	53.2	-0.18
Rohoic Creek	2-RHC000.58	3/4/2011	0.41	57.1	69.1	-1.21
		2/19/2020	0.53	39.0	65.8	-0.50
Swift Creek	2-SFT019.02	9/30/2008	0.058	70.0	81.2	-0.71
		9/29/2009	0.07	83.8	90.7	-1.13
	2-SFT019.15	3/2/2020	0.03	71.9	78.2	-0.09
	2-SFT025.32	3/10/2020	0.03	76.2	85.3	-0.09
Reference	2-JOH004.23	10/19/2005	0.31	66.3	78.5	-1.39

[1] Values in blue are in the no probability range for stressor effects. Values in green are in the low probability range for stressor effects. Values in yellow are in the medium probability range for stressor effects.

2.3. Land Use Assessment

While a more detailed land use assessment will be part of the James River Tributaries Project TMDL Report, the stressor analysis evaluated the potential connections between land use patterns within the watershed and impaired benthic stations. Table 9 shows the land uses contributing to each of the benthic monitoring stations in the James River Tributaries Project area. In general, the impaired watersheds were a mixture of impervious area, forest, and residential trees and grasses. No other land use comprised more than 10% of the land area in any of the impaired watersheds. Some watersheds, like Swift Creek and its tributaries, were majority-forested, while others had very little forest. Bailey Creek, Nuttree Branch, Oldtown Creek, Proctors Creek, and Rohoic Creek watersheds were dominated by impervious areas (as high as 28%) and residential trees and grasses.

Regression analyses were used to compare these land use trends to benthic SCI scores at the respective stations. A statistically significant regression was observed between natural log transformed SCI scores and the impervious land use category. No other land use categories were significantly correlated with benthic health. SCI scores were negatively correlated with imperviousness (-0.59 correlation coefficient). As the percentage of impervious surfaces in a watershed increased, stream health (as measured by the SCI) decreased (Figure 12). While this regression was statistically significant ($p=0.025$), it was not very strong and represented less than a third of the variability in the SCI data ($r^2 = 0.27$).

The finding that stream health is correlated with imperviousness in the watershed is consistent with Brabec *et al.* (2002), who reviewed the biological impacts of watershed imperviousness and found that fish- and macroinvertebrate diversity decreased when watersheds exceeded 3.6 to 15% imperviousness. The Bailey Creek, Nuttree Branch, Proctors Creek, and Rohoic Creek watersheds all exceed 15% imperviousness. As a watershed develops and the percentage of impervious surfaces increases, runoff during precipitation events increases. As the amount of runoff increases, peak flows in local streams increase causing streambank erosion and stream bed scouring. This scenario causes unstable habitat conditions for benthic macroinvertebrates and increased sediment loads, which could result in impairment.

Table 9. Land use upstream from each benthic monitoring station.

Stream	Station	Water	Impervious	Barren	Forest	Urban/ Res. Trees	Scrub/ Shrub	Harvested/ Disturbed	Urban/ Res. Grass	Pasture	Cropland	Other
Bailey Creek	2-BLY005.73	0.14%	28.28%	0.00%	23.95%	13.63%	1.30%	0.00%	30.68%	0.52%	1.10%	0.40%
Nuttree Branch	2-NUT000.62	0.98%	20.13%	4.93%	27.83%	20.86%	1.05%	0.00%	23.63%	0.00%	0.00%	0.59%
Oldtown Creek	2-OTC001.54	0.58%	12.63%	0.02%	33.48%	11.73%	0.38%	1.68%	23.40%	3.10%	7.54%	5.47%
	2-OTC005.38	0.69%	8.09%	0.04%	34.94%	10.61%	0.05%	2.46%	22.35%	4.17%	8.54%	8.05%
Proctors Creek	2-PCT002.46	0.78%	21.70%	0.38%	16.68%	21.55%	0.20%	0.00%	30.57%	0.84%	0.00%	7.30%
Rohoic Creek	2-RHC000.58	0.91%	17.09%	1.20%	28.40%	13.92%	0.98%	0.25%	27.23%	4.35%	2.63%	3.04%
Swift Creek	2-SFT012.84	2.60%	9.26%	0.73%	52.61%	13.84%	0.39%	0.63%	14.13%	2.53%	0.55%	2.74%
	2-SFT019.02	2.92%	10.34%	0.47%	50.57%	14.26%	0.44%	0.66%	14.78%	2.52%	0.35%	2.71%
	2-SFT019.15	2.96%	10.29%	0.48%	50.59%	14.27%	0.45%	0.67%	14.78%	2.45%	0.35%	2.72%
	2-SFT025.32	3.55%	10.75%	0.60%	48.56%	14.09%	0.51%	0.85%	15.27%	2.77%	0.30%	2.74%
Horsepen Creek	2-HEP001.27	0.00%	0.20%	0.00%	95.79%	0.41%	0.00%	1.47%	0.38%	0.00%	0.00%	1.76%
Licking Creek	2-LIA000.50	1.41%	5.62%	0.00%	62.32%	12.76%	0.26%	0.46%	11.56%	2.78%	0.07%	2.76%
Otterdale Branch	2DOTD002.52	0.09%	1.95%	0.00%	81.67%	4.60%	0.00%	2.52%	6.81%	1.56%	0.00%	0.80%
Third Branch	2DTRO001.88	0.07%	8.93%	0.00%	51.34%	20.71%	0.65%	0.00%	13.92%	2.53%	0.39%	1.47%
Jones Creek (reference)	2-JOH004.04	0.78%	4.07%	0.00%	61.54%	16.74%	0.32%	1.65%	7.68%	0.81%	1.48%	4.94%

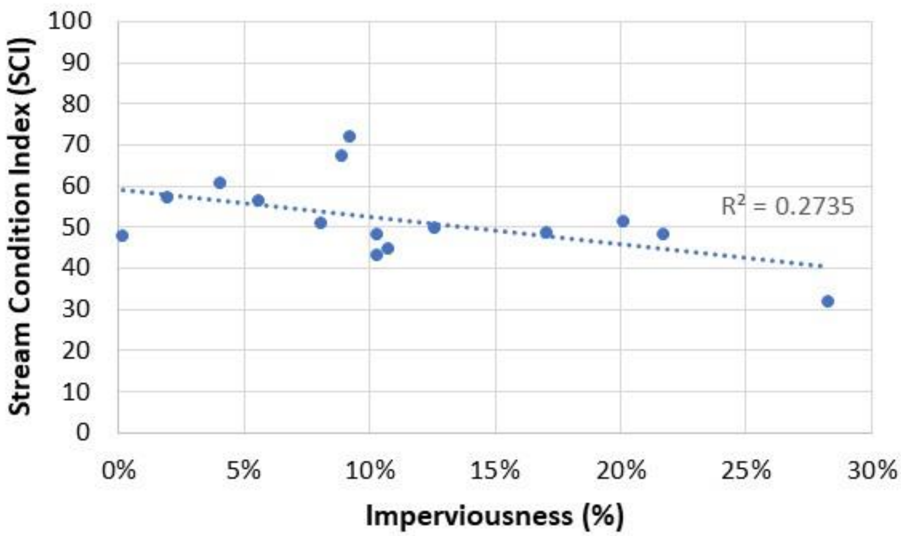

Figure 12. Regression between imperviousness in the watershed and benthic health.

2.4. Water Quality Data Assessment

Water quality data for all of the candidate stressors were evaluated to assess trends and compare to relevant water quality standards and stressor thresholds.

2.4.1. Temperature

Temperature data for the James River Tributaries Project streams are available from VDEQ measurements and JMU diurnal deployments. VDEQ measures temperature when collecting benthic or water quality samples, so periodic temperature data are available from 2000 to present at the impaired benthic stations (Figure 13) and other water quality stations on the impaired streams and associated tributaries. Temperatures obviously vary by season, so ranges are wide when year-round measurements are considered. Overall, none of the benthic stations had temperature measurements above the water quality standard of 32°C for the Piedmont Region. The maximum recorded temperature at impaired benthic stations was 29.09°C in Swift Creek (2-SFT019.15). This was also the only benthic station to have statistically significant higher temperatures than the reference station ($p<0.05$ in t-test with unequal variances).

In addition to the impaired benthic stations, temperature data from 43 other stations within the impaired watersheds were analyzed. None of those stations exceeded the Virginia water quality standards for temperature.

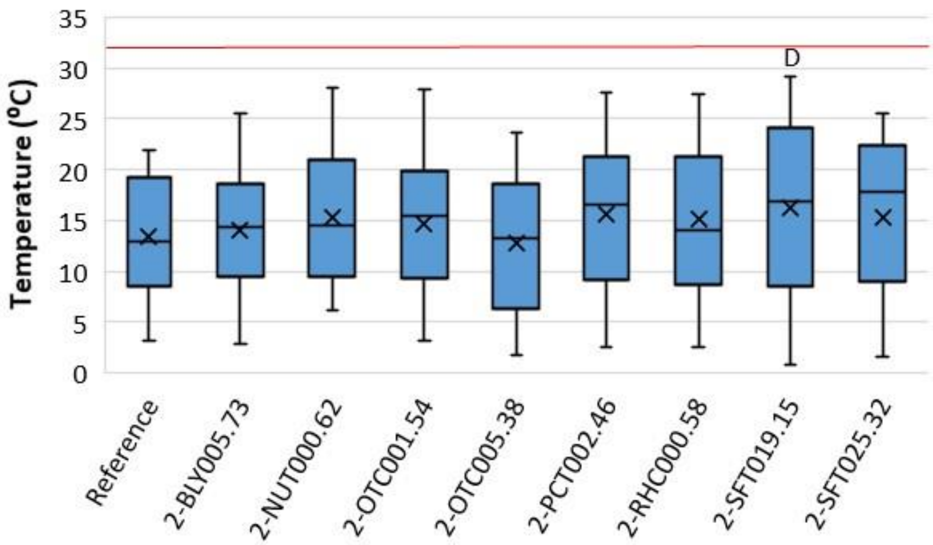

Figure 13. Temperature at impaired and reference benthic stations in James River Tributaries Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represent the mean. The "D" indicates a statistically significant difference from the reference station. The red line represents the Virginia water quality standard.

JMU also collected diurnal temperature at each of the primary benthic stations during the summer of 2020. Diurnal data were collected at 15-minute intervals for 1 week at each location. Temperature data during diurnal deployments are shown in Figure 14. Diurnal temperatures exhibited the natural cycle of increases during the day from solar heating and decreases at night. No stations exceeded the Virginia water quality standard of 32ºC. At all stations, the daytime maximum temperature was below 30ºC. This is an indication that temperature is not a primary stressor in these streams.

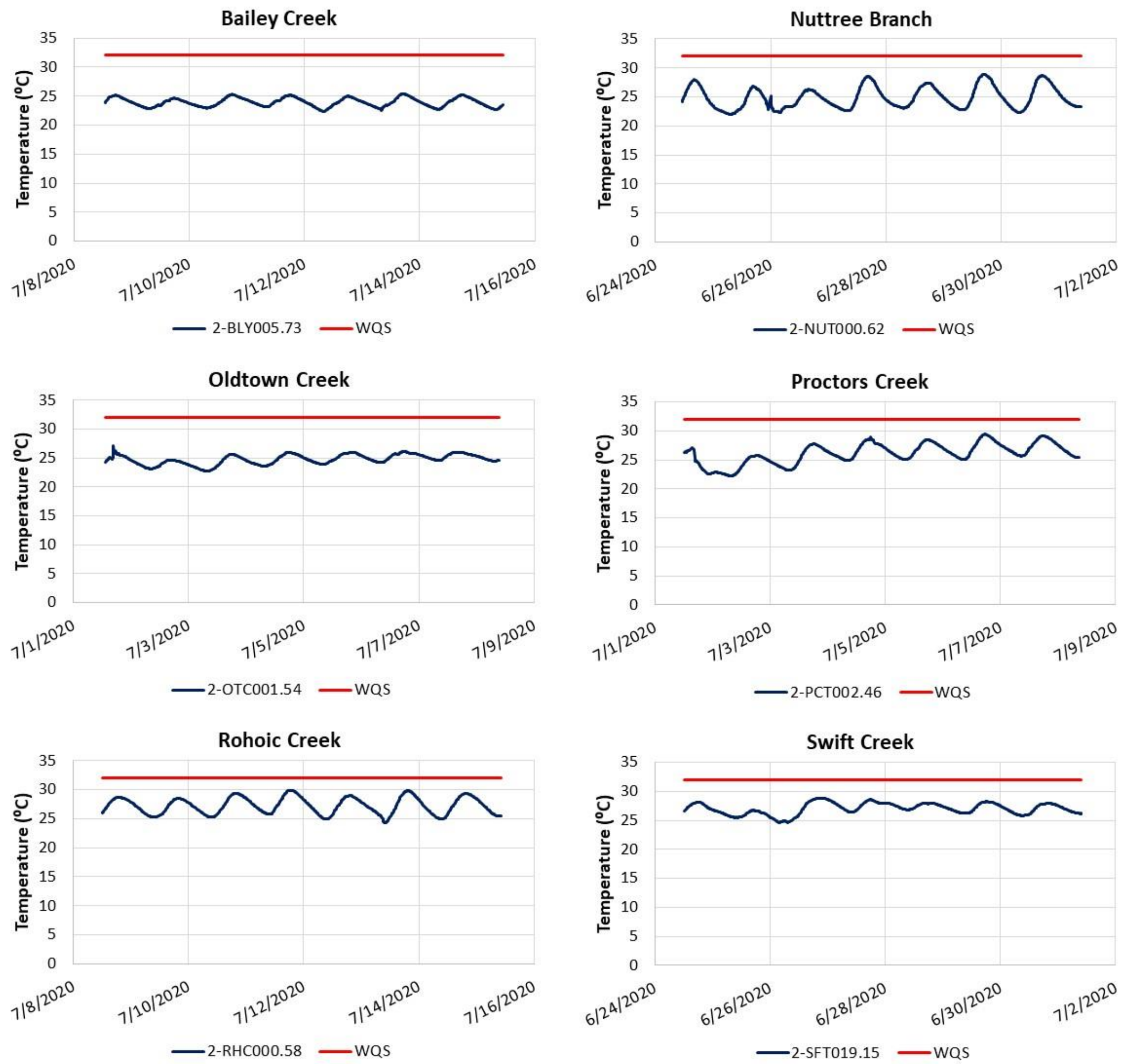

Figure 14. Diurnal temperature conditions in James River Tributaries Project streams. The red line represents the Virginia water quality standard.

2.4.2. pH

VDEQ measures pH when collecting benthic or water quality samples, so periodic pH data are available from 2000 to present at the impaired benthic stations (Figure 15) and other water quality stations on the impaired streams and associated tributaries. Measured pH values were slightly below neutral at all stations and averaged from 6.38 in Oldtown Creek (2-OTC005.38) to 6.96 in Rohoic Creek. These two stations were statistically different from the reference site ($p<0.05$ in t-test with unequal variance), with Oldtown Creek having lower pH than the reference and Rohoic Creek having higher pH than the reference.

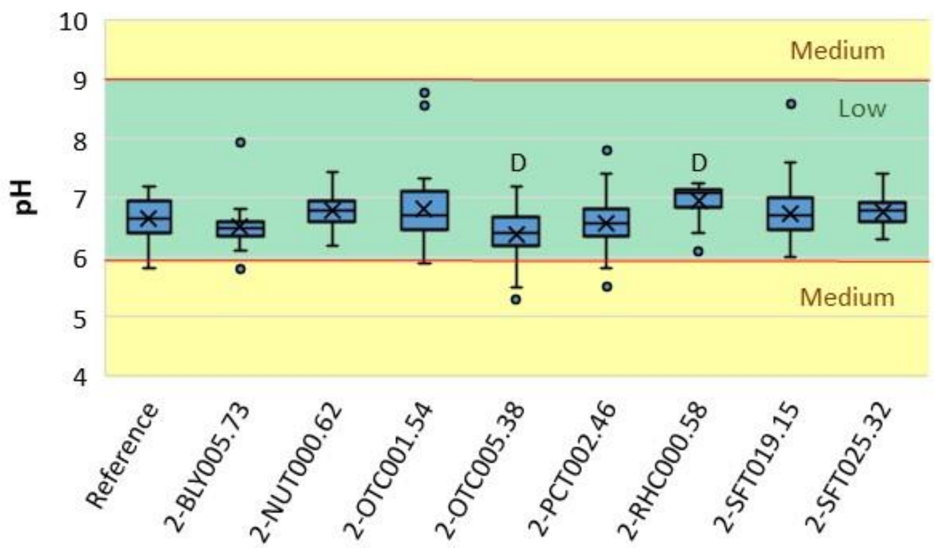

Figure 15. pH in James River Tributaries Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represent the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the reference station. The red line represents the Virginia water quality standard. Colors represent the probability that data within that range would be responsible for causing stress.

Average pH values were all within the water quality standards of 6.0-9.0 SU and were within the range identified by VDEQ as low probability for producing stressor effects (VDEQ, 2017), however, some individual pH results were outside of these ranges. pH values below 6.0 were observed in Bailey Creek (1/40 samples or 2.5%), Oldtown Creek (7/68 samples or 10.3%), and Proctors Creek (5/71 samples or 7.0%). Frequency and timing of these low pH excursions are shown in Figure 16. Minimum pH values in these streams were 5.8, 5.3, and 5.4, respectively. With the lowest pH and over 10% of samples below pH 6.0, Oldtown Creek is also listed in the 2018 Water Quality Assessment with a pH impairment (VDEQ, 2020). Low pH in this stream could be contributing to stress in the benthic community.

In addition to the impaired benthic stations, pH data from 43 other stations within the impaired watersheds were analyzed. Of those, stations on Nuttree Branch (2-NUT002.22) and Swift Creek

(2-SFT019.02, and 36.00) also had pH values below the minimum water quality standard of 6.0 SU. However, combining all samples from these streams, only 2/52 samples (3.8%) in Nuttree Branch and 3/1067 (0.3%) in Swift Creek were below a pH 6.0 SU.

In addition, a number of tributaries had pH values below the minimum water quality standard of 6.0 SU. Both monitored tributaries to Proctors Creek (Great Branch and Redwater Creek) had pH values below 6.0. In Great Branch, 5/22 samples (23%) were below 6.0 with a minimum pH of 5.16. In Redwater Creek, only 1/13 samples (7.7%) were below 6.0 with a minimum of 5.6. Low pH in these tributaries could be contributing to low pH in Proctors Creek.

Nine Swift Creek tributaries had pH values below the minimum water quality standard of 6.0 SU. Of these, Horsepen Creek and Church Branch had low pH that averaged 5.69 and 5.22, respectively. In Horsepen Creek, 8/11 samples (73%) were below 6.0 with a minimum of 4.94. In Church Branch, 19/23 samples (83%) were below 6.0 with a minimum of 3.8. These low pH tributaries are certainly contributing to lower pH values in Swift Creek, however, pH levels in Swift Creek have consistently been within the low probability range for stressor effects.

JMU also collected diurnal pH at each of the primary benthic stations during the summer of 2020. Diurnal data were collected at 15-minute intervals for 1 week at each location. pH data during diurnal deployments are shown in Figure 17. Diurnal pH values in some streams (particularly Nuttree Branch and Rohoic Creek) exhibited a natural cycle of increases during the day while plants are photosynthesizing and decreases at night while respiration dominates. This indicates the influence of algae on water quality in these streams. Diurnal data also shows brief interruptions of daily pH patterns by storm events that either increase pH (as in Nuttree Branch and Oldtown Creek) or decrease pH (as in Proctors Creek). During the week of diurnal monitoring, pH values in all of the streams except for Proctors Creek remained within the water quality standards. In Proctors Creek, pH values dropped below the water quality standard of 6.0 after a storm event on the first day of monitoring (4.74 SU) and did not recover to above 6.0 SU until day 5. pH averaged only 5.82 in Proctors Creek during the week and was below 6.0 SU for 64% of the time.

The low pH in Proctors Creek and the upstream station in Oldtown Creek may be due to these streams' natural connection to low-lying wetlands. In these permanently or periodically flooded wetlands, oxygen is quickly depleted and decomposition of dense organic matter proceeds through alternative anaerobic pathways (Inglett *et al.*, 2005). Some of these pathways, such as fermentation, can lead to the production of organic acids. Others, such as sulfate reduction and methanogenesis, can produce hydrogen ions as a biogeochemical byproduct. The result can be an increase in acidity and decrease in pH. This condition is likely occurring in Proctors Creek and Oldtown Creek due to the following observed evidence.

- The Proctors Creek and Oldtown Creek watersheds contain a large number of wetland and hardwood swamps. Table 10 shows the acreage and land use percentage of wetlands in each of the James River Tributaries Project watersheds. Proctors Creek and Oldtown Creek watersheds contain 6.48% and 6.10% wetlands respectively, with the majority of these being forested/shrub wetlands in close connection to the main channel (Figure 18 and Figure 19). Other streams in the project only contain 1.37% to 4.49% wetlands. The abundance of connected wetlands in Proctors Creek and Oldtown Creek may be the source of anaerobic decomposition and organic acid production.
- pH in Proctors Creek decreased following a storm event. The storm event would inundate and/or flush water from connected wetlands that may have been accumulating organic acids, thus lowering the pH in the mainstem.
- Proctors Creek and Oldtown Creek exhibit the characteristic dark tannin color of blackwater swamps. This color is the result of organic tannins and other dissolved organic matter from the decomposition of wood and leaf litter material.
- Tributaries to Proctors Creek (Great Branch and Redwater Creek) also exhibit low pH and dark tannin staining of the water.

In summary, low pH may be a stressor to the benthic community in Oldtown Creek and Proctors Creek. Oldtown Creek exhibited pH values as low as 5.3, and more than 10% of samples were below 6.0 SU. In Proctors Creek, 7% of DEQ samples were below 6.0 SU, with a minimum of 5.4. During diurnal sampling, Proctors Creek exhibited a minimum pH of 4.74 and pH below 6.0 for 64% of the time. Both monitored tributaries in Proctors Creek also exhibited low pH conditions. Low pH is not likely a stressor in Bailey Creek, Nuttree Branch, and Swift Creek. Even though some samples and tributaries to these streams exhibited low pH, the impact on the benthic stations appeared to be limited. Low pH is not a stressor in Rohoic Creek. In fact, pH in Rohoic Creek was statistically higher than in the reference stream. No values were below or above the water quality standard or outside the low probability range for stressor effects.

An analogous and related parameter to pH is alkalinity. Alkalinity is the capacity of a water to neutralize an acid. Typically, as alkalinity decreases, pH decreases. This is because the primary components of alkalinity (OH^-, HCO_3^-, and CO_3^{-2}) are in short supply and do not have the capacity to neutralize large quantities of acid. If acids are added to the stream under these conditions, pH will drop because it is not neutralized. Alkalinity was measured periodically in some James River Tributary Project streams (Table 11). Alkalinity ranged from 10.9 mg/L in Oldtown Creek to 53.1 mg/L in Bailey Creek. Compared to the reference and the other streams, Oldtown Creek had the lowest alkalinity. This is consistent with the low pH values that were observed in Oldtown Creek.

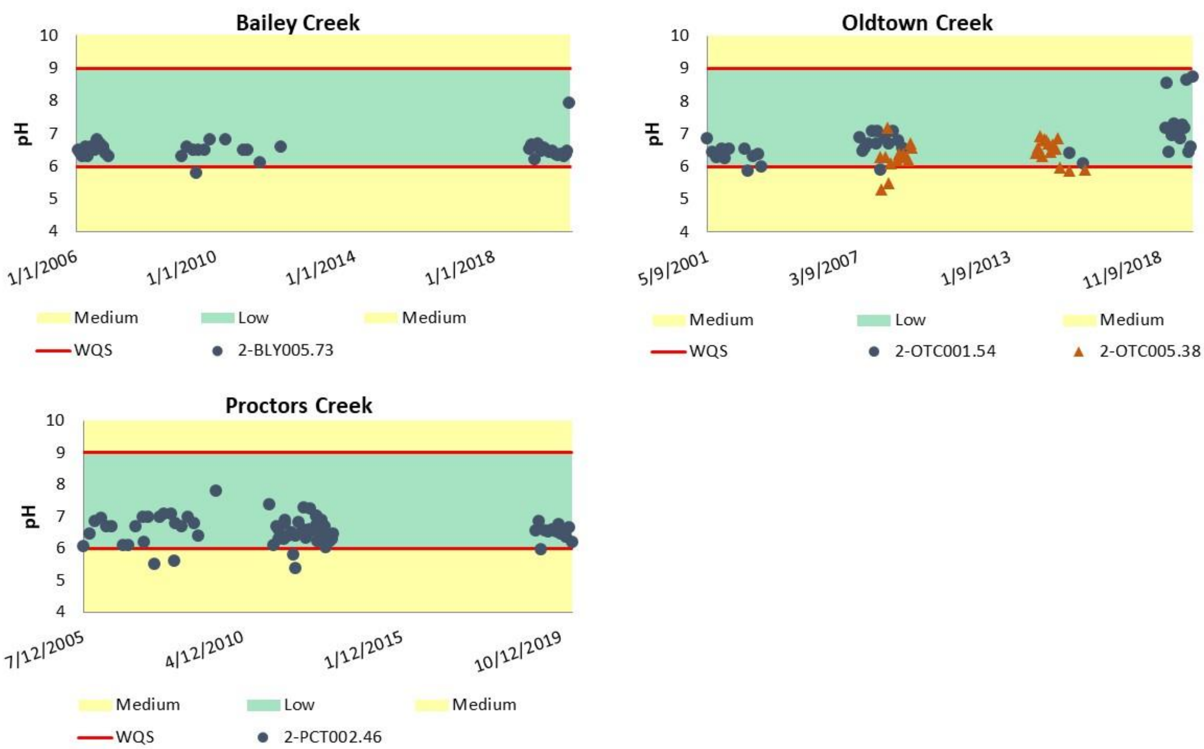

Figure 16. pH in Bailey Creek, Oldtown Creek, and Proctors Creek. The red line represents the Virginia water quality standard. Colors represent the probability that data within that range would be responsible for causing stress.

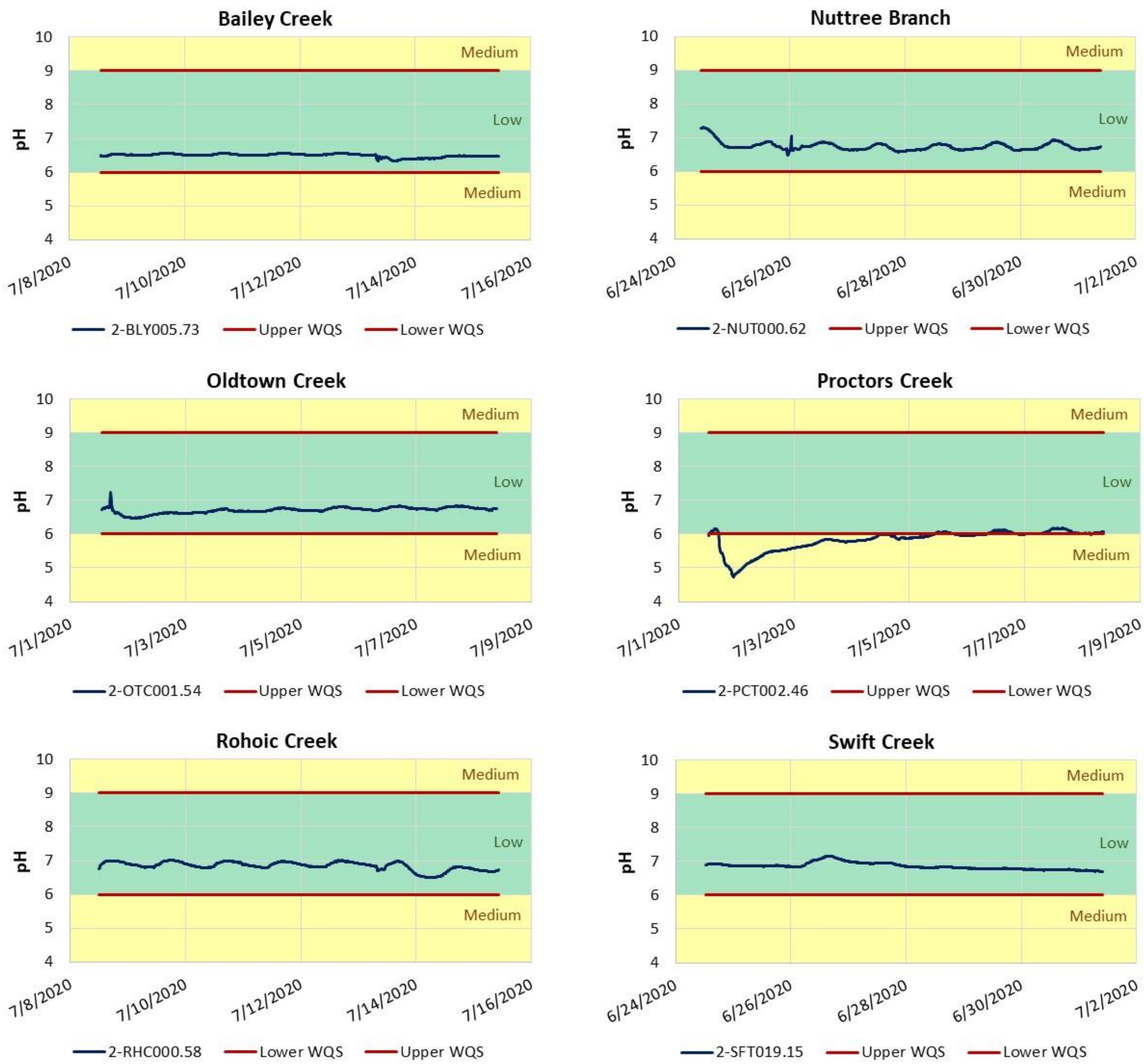

Figure 17. Diurnal pH conditions in James River Tributaries Project streams. The red line represents the Virginia water quality standard. Colors represent the probability that data within that range would be responsible for causing stress.

Table 10. Acreage and percentage of wetlands in James River Tributaries Project watersheds.

Stream	Emergent Wetland		Forested/Shrub Wetland		Total Wetlands	
	Acres	%	Acres	%	Acres	%
Bailey Creek	96	1.05%	316	3.44%	412	4.49%
Nuttree Branch	3	0.07%	49	1.30%	52	1.37%
Oldtown Creek	32	0.38%	481	5.71%	514	6.10%
Proctors Creek	56	0.49%	683	5.99%	739	6.48%
Rohoic Creek	32	0.51%	174	2.82%	206	3.33%
Swift Creek	160	0.23%	2231	3.20%	2391	3.43%

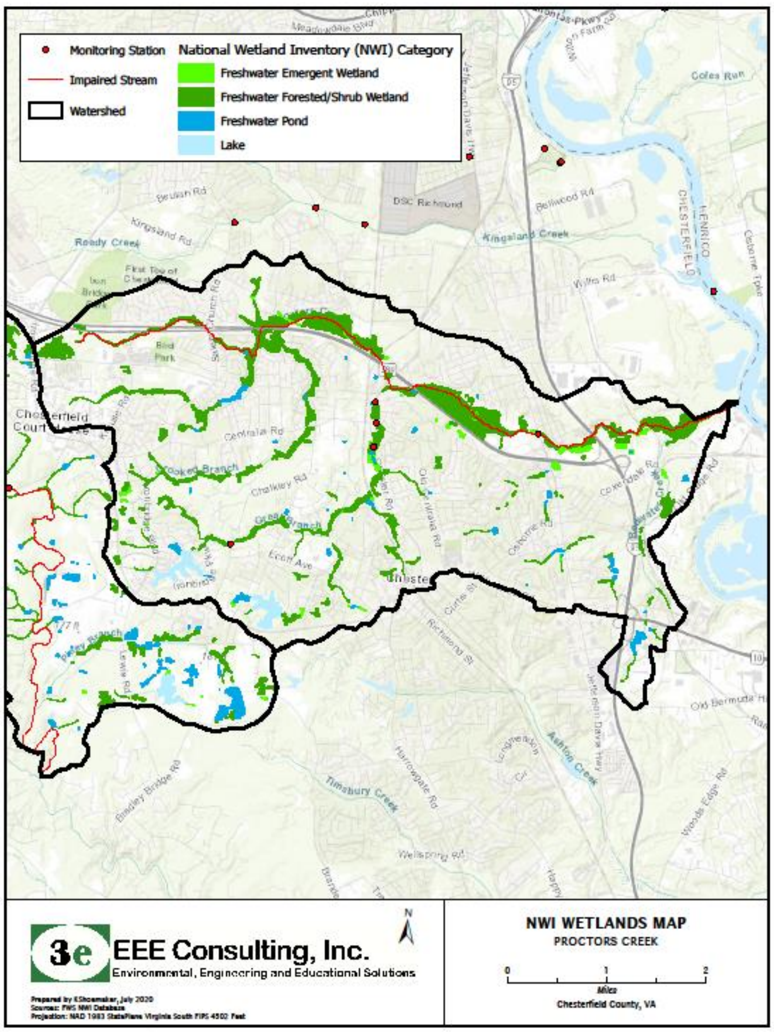

Figure 18. Wetlands in the Proctors Creek watershed.

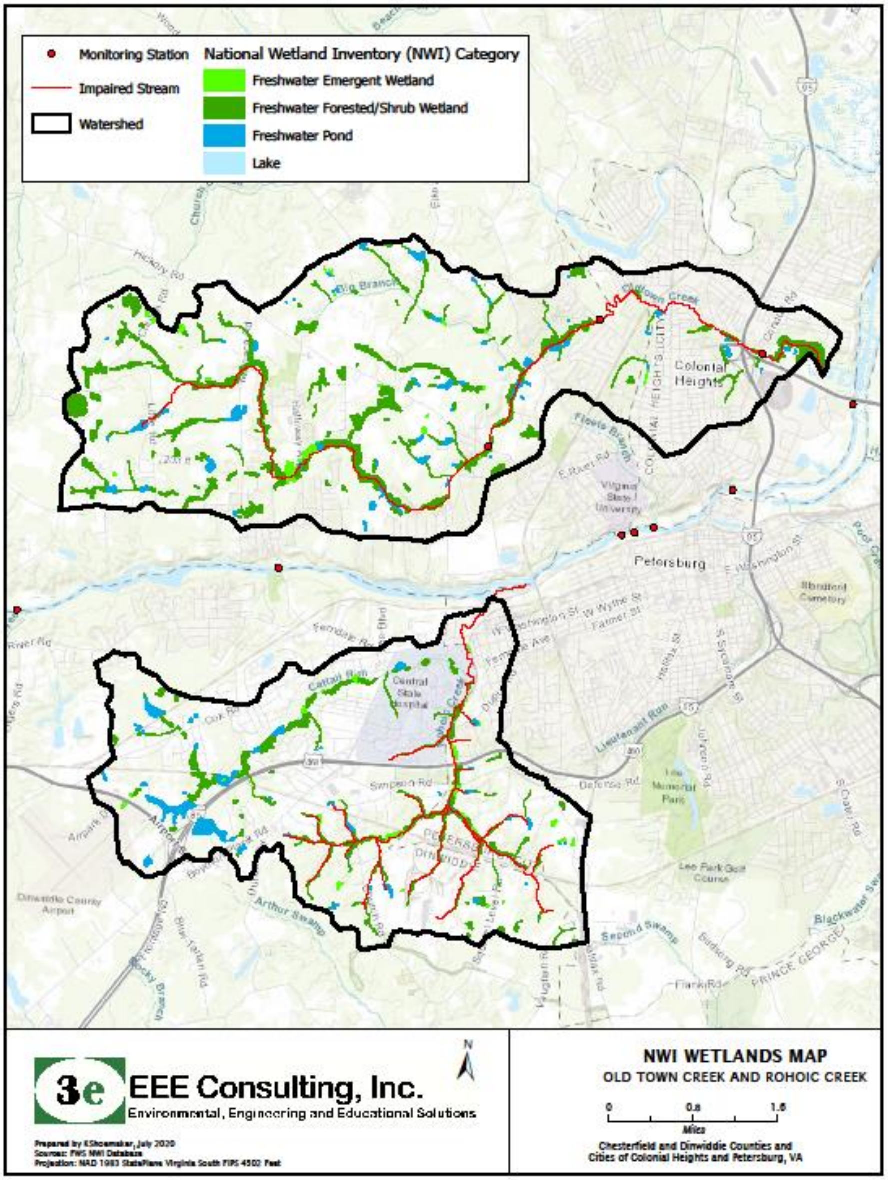

Figure 19. Wetlands in the Oldtown Creek watershed.

Table 11. Alkalinity in the James River Tributaries Project streams.

Stream	Station	N	Average Alkalinity (mg/L as $CaCO_3$)
Bailey Creek	2-BLY000.65	16	53.1
Nuttree Branch	2-NUT000.62	1	20.6
Oldtown Creek	2-OTC001.54	1	10.9
Rohoic Creek	2-RHC000.58	1	20.6
Swift Creek	2-SFT004.92	7	18.8
	2-SFT019.02	2	18.7
	2-SFT019.15	8	18.9
	2-SFT022.14	6	16.8
Reference	2-JOH004.23	1	25.0

2.4.3. Dissolved Oxygen

VDEQ measures dissolved oxygen (DO) when collecting benthic or water quality samples, so periodic DO data are available from 2000 to present at the impaired benthic stations (Figure 20) and other water quality stations on the impaired streams and associated tributaries. Average dissolved oxygen levels ranged from 7.75 mg/L in Swift Creek (2-SFT025.32) to 10.18 mg/L in Rohoic Creek (2-RHC000.58). Average values were in the medium probability range for stressor effects in Oldtown Creek and Swift Creek. Means for all other streams were in the low to no probability range for stressor effects. Bailey Creek, Oldtown Creek (at 2-OTC001.54), Proctors Creek, and Swift Creek (at 2-SFT019.15 and 2-SFT025.32) had statistically lower DO than the reference station ($p<0.05$ in t-test with unequal variance).

All stations had DO excursions into the high probability range for stressor effects, however, these excursions were more common and more severe in Oldtown Creek, Proctors Creek, and Swift Creek. Each of these streams had excursions below the Virginia water quality standard daily average of 5.0 mg/L and below the minimum of 4.0 mg/L. Figure 21 shows the time series of DO concentrations in each impaired stream. Bailey Creek, Nuttree Branch, and Rohoic Creek had excursions into the high probability range for stressor effects but no excursions below the water quality standard. In Oldtown Creek, 29% of DO values were in the high probability range for stressor effects, and 16% of data were below the water quality standard. In Proctors Creek, 20% of DO values were in the high probability range for stressor effects, and 3% of data were below the water quality standard. In Swift Creek, 44% of DO values were in the high probability range for stressor effects, and 25% of data were below the water quality standard. Minimum DO values in Oldtown Creek, Proctors Creek, and Swift Creek were 0.1, 2.3, and 0.47 mg/L, respectively. These low DO values certainly have the potential to cause stress conditions on benthic macroinvertebrate communities.

Low DO conditions were typically observed during the summer months when temperatures are high and flows are typically low. Figure 22 shows monthly DO conditions in each stream from 2018 and 2019. DO levels dropped to the high probability range for stressor effects during the summer and fall months in each stream, except for Rohoic Creek. DO conditions in Swift Creek were the most critical, with levels dropping below 5.0 mg/L for the months of July through October in 2018 and 2019.

In addition to the impaired benthic stations, DO data from 43 other stations within the impaired watersheds were analyzed. These data confirmed low DO conditions in the Swift Creek and Proctor Creek watersheds and revealed low DO excursions at water quality stations in Bailey Creek, Nuttree Branch, and Rohoic Creek. No other monitoring stations were present within the Oldtown Creek watershed.

Even though DO excursions below 5.0 mg/L were not observed at the benthic monitoring stations on Bailey Creek, Nuttree Branch, and Rohoic Creek, other stations on these streams did experience DO excursions. Station 2-BLY003.42 on Bailey Creek, downstream from the benthic station, had 7.3% of data below the 5.0 mg/L DO standard. In Nuttree Branch and Rohoic Creek, upstream stations 2-NUT002.22 and 2-RHC02.23 had 20% and 10% of data below the 5.0 mg/L DO standard, respectively.

Within the Proctors Creek watershed, both of the monitored tributaries (Great Branch and Redwater Creek) exhibited DO below the 5.0 mg/L water quality standard. DO levels were below 5.0 mg/L 32% of the time in Great Branch and 31% of the time Redwater Creek. Within the Swift Creek watershed, multiple other Swift Creek stations and tributaries violated the 5.0 mg/L water quality standard. Swift Creek stations 2-SFT004.92, 2-SFT027.38, 2-SFT030.65, and 2-SFT036.00 had 4.3%, 33%, 50%, and 12% of data below 5.0 mg/L DO. This includes only free-flowing Swift Creek stations and excludes stations within impoundments, all of which exhibited low DO at depth. The following Swift Creek tributaries also exhibited DO levels below 5.0 mg/L: Blackman Creek, Church Branch, Franks Branch, Long Swamp, Second Branch, Spring Run, Timsbury Creek, and an unnamed tributary to Swift Creek. This represents over half of the 14 monitored Swift Creek tributaries. It should be noted that at Swift Creek station 2-SFT012.84, where the benthic community is unimpaired, DO averaged 9.36 mg/L and never violated the 5.0 mg/L DO standard.

In addition to periodic dissolved oxygen measurements, JMU collected diurnal dissolved oxygen data at each of the primary benthic stations during the summer of 2020. Diurnal data were collected at 15-minute intervals for 1 week at each station. Diurnal monitoring of dissolved oxygen is important, because critical dissolved oxygen levels are typically encountered just before sunrise. This is due to the combination of oxygen consumption from respiration and the absence of oxygen production from photosynthesis during the night. Diurnal monitoring was conducted in late June through July, because critical dissolved oxygen levels are also more common during the hot and dry summer months.

Dissolved oxygen data during diurnal deployments are shown in Figure 23. Diurnal dissolved oxygen values at all stations exhibited the natural cycle of increases during the day while plants are photosynthesizing and decreases at night while respiration dominates. Dissolved oxygen levels in Nuttree Branch and Proctors Creek were in the high probability range for stressor effects at night, but were in the medium to low probability range during the day. Minimum DO levels did not dip below 6.0 mg/L in either of these streams, so there were no violations of the daily average DO standard of 5.0 mg/L or the minimum DO standard of 4.0 mg/L. In Bailey Creek, Oldtown Creek, and Rohoic Creek, DO levels were consistently within the high probability range for stressor effects. Nighttime DO levels dropped below 5.0 mg/L on one occasion in Oldtown Creek and Rohoic Creek, but daily average DO never dropped below the daily average standard of 5.0 mg/L and minimums never dropped below the minimum DO standard of 4.0 mg/L. Rohoic Creek also exhibited the largest daytime to nighttime swings in DO. Particularly after a storm event on Day 6, DO levels swung by nearly 4 mg/L from day to night. This is an indication of nutrient enrichment and excess algae growth.

In Swift Creek, DO levels were the most critical. DO was almost exclusively in the high probability range for stressor effects (night and day). DO in Swift Creek also violated both the daily average DO standard and the daily minimum standard. The daily average DO standard of 5.0 mg/L was violated on 4 of the 7 days, with daily averages ranging as low as 4.25 mg/L. In fact, for the final

3 days of the deployment, DO levels did not go above the 5.0 mg/L daily average standard. The minimum DO standard of 4.0 mg/L was violated on 2 days of the deployment, with daily minimums dropping to 3.82 and 3.50 mg/L, respectively.

Figure 24 shows the diurnal dissolved oxygen data expressed as percent saturation. This method of analysis allows the observed DO to be compared with the anticipated DO if the stream were at full DO saturation. Values above 100% mean that the stream is super-saturated with DO, and values below 100% show that oxygen is depleted to varying degrees. Large swings in DO during a day indicate that nutrient enrichment may be driving high levels of photosynthesis by algae during the day and oxygen consumption at night. Two of the streams (Nuttree Branch and Rohoic Creek) exhibited these large swings of DO indicative of nutrient enrichment and excess algal growth. The other streams experienced much more modest swings in DO, and DO suppression is likely from a combination of organic matter decomposition and low slope, which limits reoxygenation. Measures of organic matter (total volatile solids and total organic carbon) were relatively high for each of the streams except for Swift Creek. This could explain depressed DO in Bailey Creek, Oldtown Creek, and Proctors Creek. All of the impaired streams also have relatively low slopes. This is most noticeable in Swift Creek, where the slope in the impaired reach is only 0.0002 ft/ft. This is only half the slope of the unimpaired Swift Creek reach and one fifth the slope of any of the other streams in the project (Table 12). This low slope along with upstream impoundments could explain the low DO levels in Swift Creek.

In summary, dissolved oxygen is almost certainly a stressor in Swift Creek. Minimum measured DO values were near zero, 25% of periodic measurements were below 5.0 mg/L, and diurnal DO measurements violated both the daily average DO standard and the daily minimum DO standard. Low DO in Swift Creek is likely a combination of very low stream slope, upstream impoundments that slow water and increase depth and temperature, decomposition of organic matter in deposited sediments, and possibly nutrient enrichment. Dissolved oxygen is likely a stressor in Oldtown Creek, where minimum DO values were near zero, 16% of periodic measurements were below 5.0 mg/L, and diurnal monitoring showed brief excursions below 5.0 mg/L. In Proctors Creek, DO is also likely a stressor. In this stream, minimum DO values were as low as 2.3 mg/L, 3% of periodic measurements were below 5.0 mg/L, but diurnal monitoring did not show excursions below 6.0 mg/L. In Oldtown Creek and Proctors Creek, low DO is likely due to decomposition of dissolved or deposited dissolved organic matter. Dissolved oxygen may be a stressor in the remaining streams (Bailey Creek, Nuttree Branch, and Rohoic Creek). Periodic DO monitoring at the benthic stations on these streams did not show excursions below 5.0 mg/L, but other monitoring stations on these streams did. Diurnal DO monitoring showed one brief excursion below 5.0 mg/L in Rohoic Creek, but none in Bailey Creek and Nuttree Branch, although nighttime levels were in the high probability range for stressor effects in all three streams. Low DO in Bailey Creek is likely from decomposition of dissolved or deposited organic matter, while low DO in Nuttree Branch and Rohoic Creek may be more driven by nutrient enrichment.

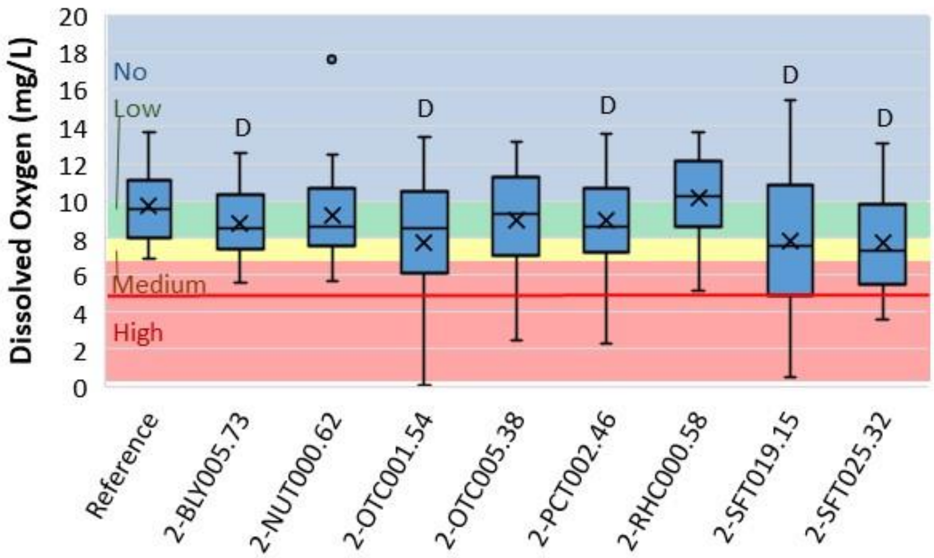

Figure 20. Dissolved oxygen in James River Tributaries Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represent the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the reference station. The red line represents the Virginia water quality standard. Colors represent the probability that data within that range would be responsible for causing stress.

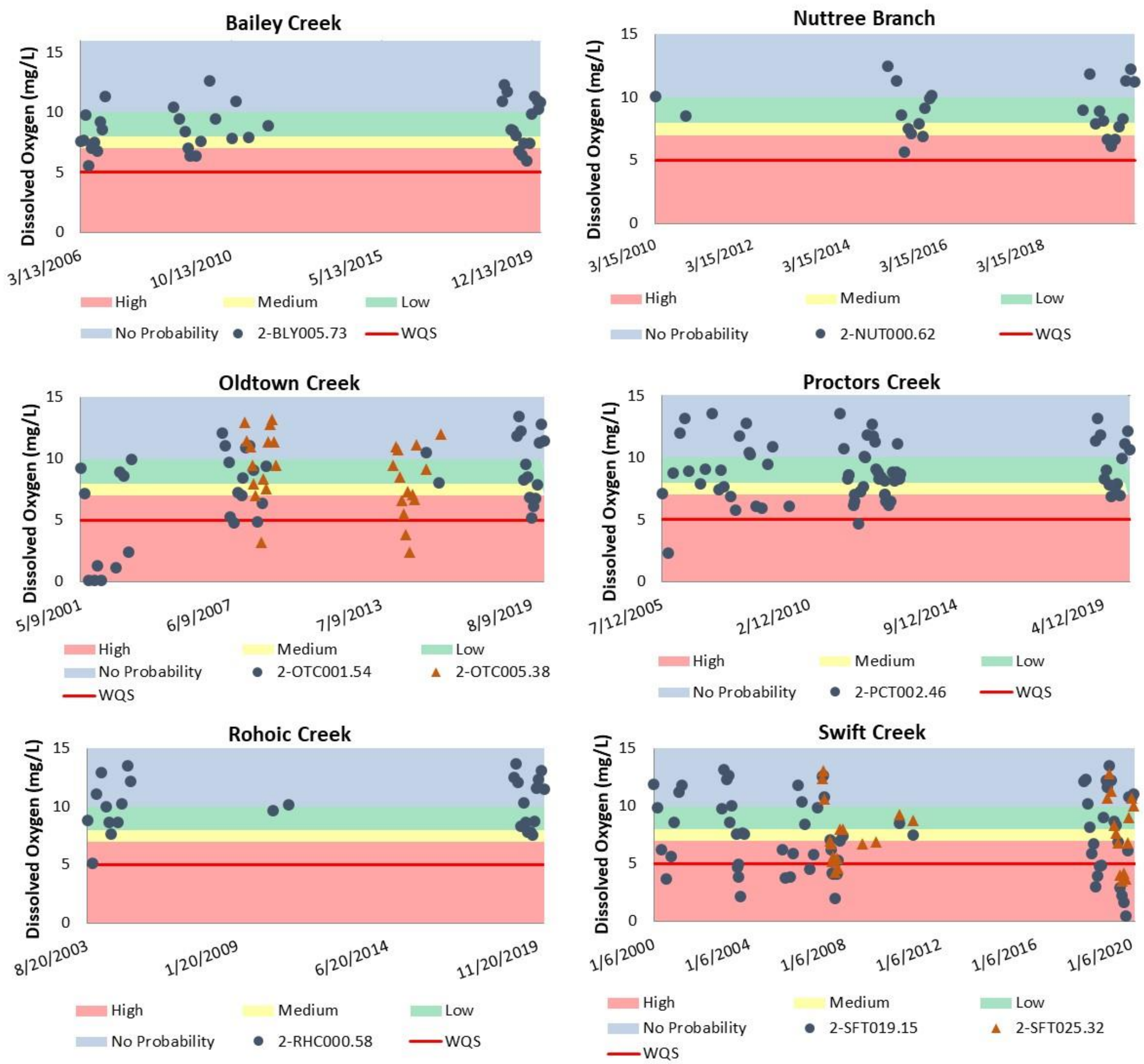

Figure 21. Dissolved oxygen over time in James River Tributaries Project streams. The red line represents the Virginia water quality standard. Colors represent the probability that data within that range would be responsible for causing stress.

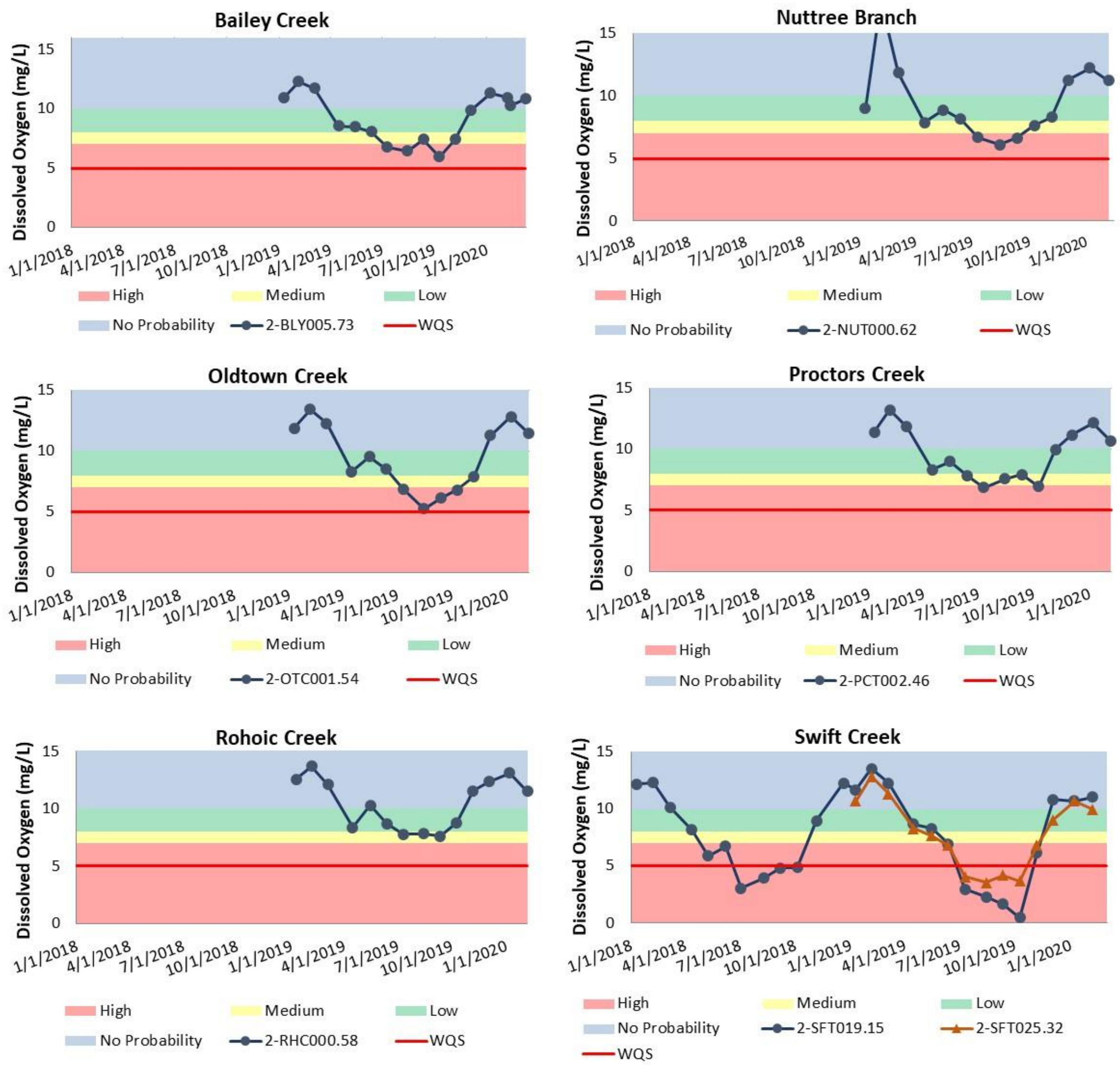

Figure 22. Dissolved oxygen in 2018 and 2019 in James River Tributaries Project streams. The red line represents the Virginia water quality standard. Colors represent the probability that data within that range would be responsible for causing stress.

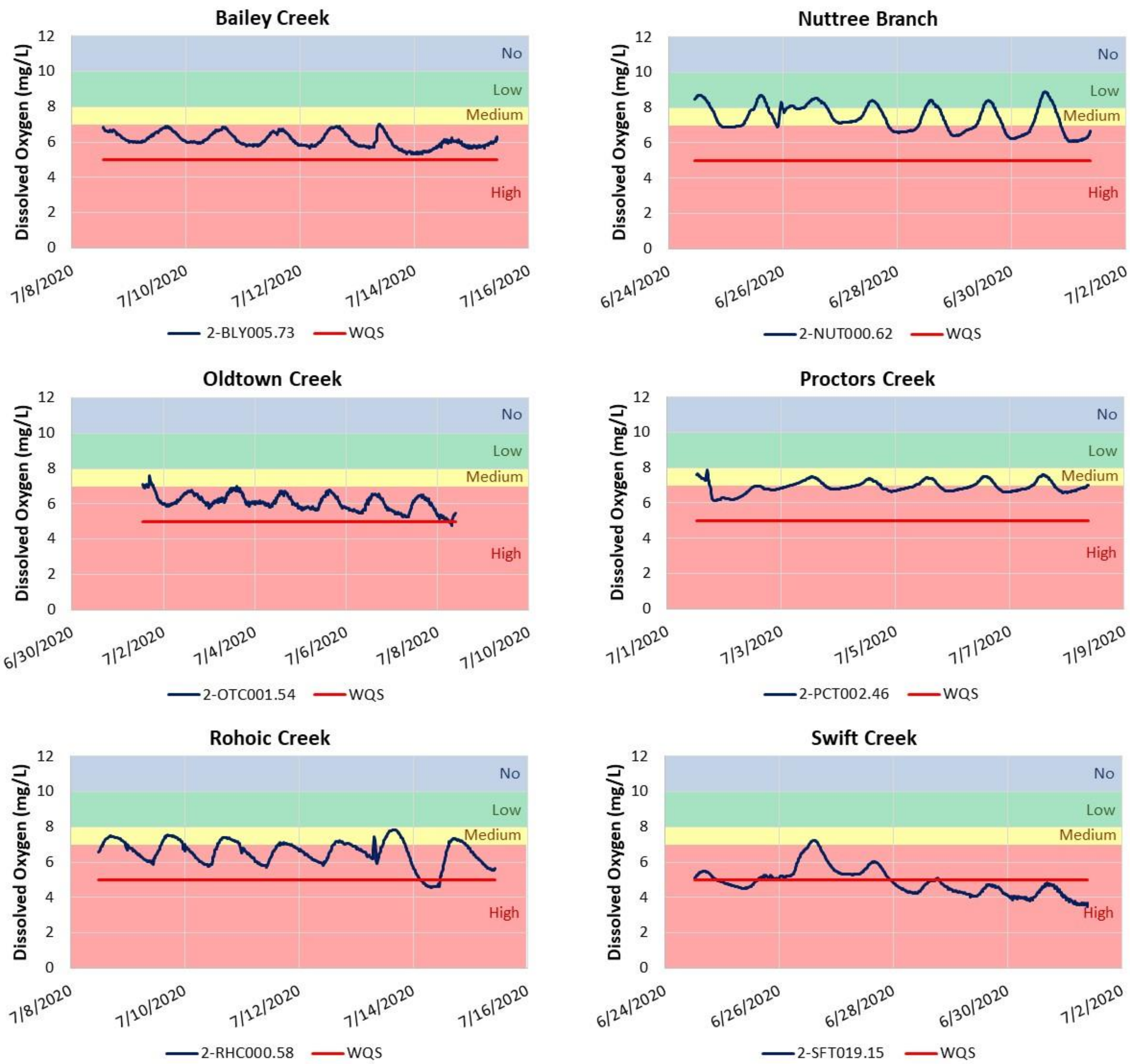

Figure 23. Diurnal dissolved oxygen conditions in James River Tributaries Project streams. The red line represents the Virginia water quality standard. Colors represent the probability that data within that range would be responsible for causing stress.

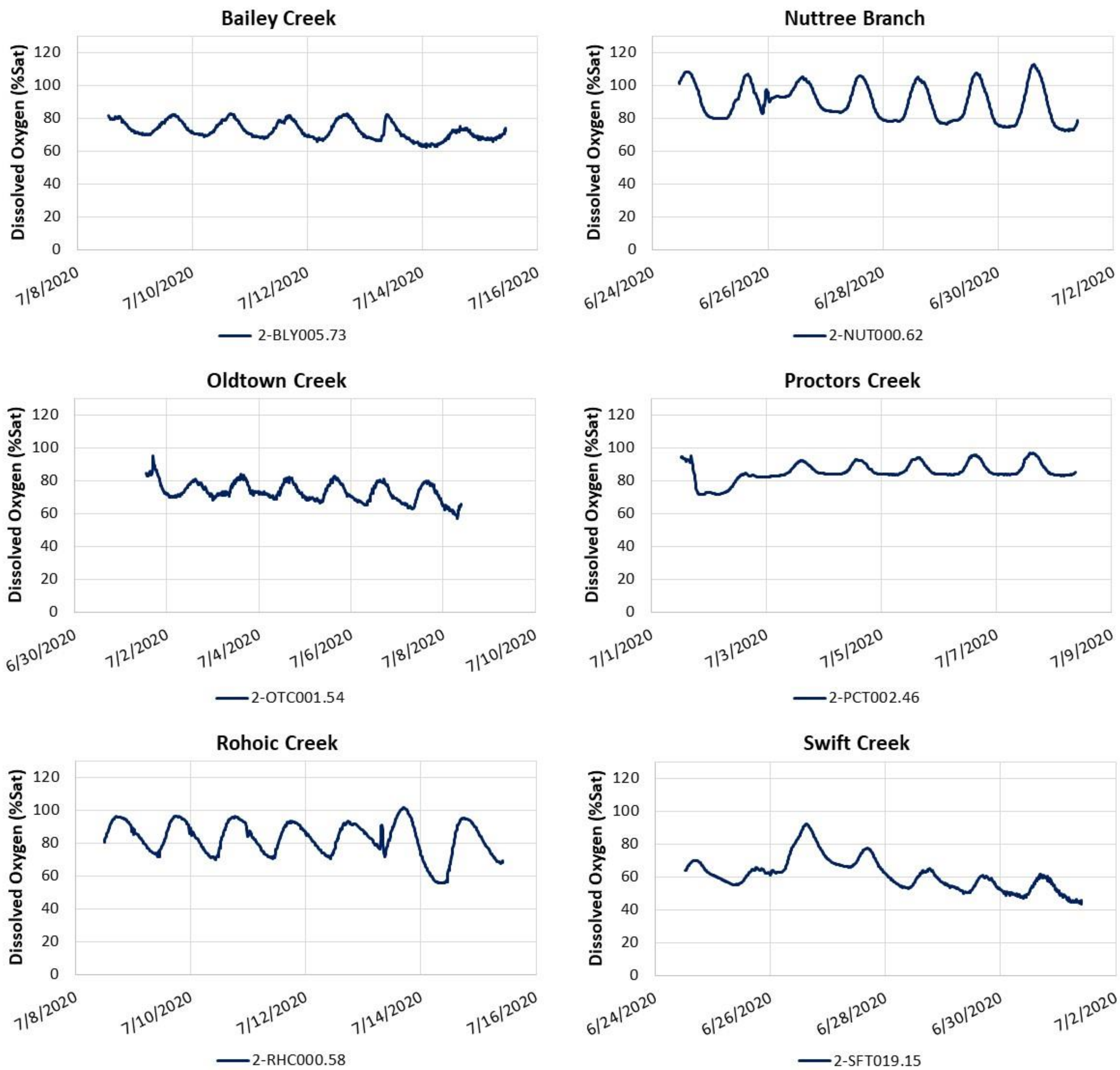

Figure 24. Dissolved oxygen in James River Tributaries Project streams expressed as percent saturation.

Table 12. Stream slope in James River Tributaries Project streams.

Stream	Slope (ft/ft)
Bailey Creek	0.0011
Nuttree Branch	0.0016
Oldtown Creek	0.0010
Proctors Creek	0.0013
Rohoic Creek	0.0013
Swift Creek (impaired)	0.0002
Swift Creek (unimpaired)	0.0004
Reference	0.0011

2.4.4. Conductivity and Total Dissolved Solids

Conductivity is a measure of the electrical potential of water based on the ionic charges of dissolved compounds. For this reason, the conductivity of water is closely related to the total dissolved solids present. VDEQ measures conductivity when collecting benthic or water quality samples, so periodic conductivity data are available from 2000 to present at the impaired benthic stations (Figure 25) and other water quality stations on the impaired streams and associated tributaries. Average conductivity at impaired benthic stations ranged from 67 uS/cm in Oldtown Creek to 256 uS/cm in Nuttree Branch. All stations, except for Oldtown Creek (2-OTC005.38), had statistically higher conductivity ($p<0.05$ in t-test with unequal variance) than the reference site, however conductivity was particularly low in the reference, averaging only 70 uS/cm. Despite being statistically higher than the reference, all stations (except for Nuttree Branch) had average conductivities in the no probability range for stressor effects. Average conductivity in Nuttree Branch was in the low probability range for stressor effects. Only two samples were in the high probability range for stressor effects. A conductivity of 1127 uS/cm was recorded in Nuttree Branch on 2/4/2019, and a conductivity of 640 uS/cm was recorded in Rohoic Creek on 11/18/2010 (which was on the day of benthic sample collection in Rohoic Creek). On both of these occasions, a precipitation event was recorded at Richmond International Airport within 72 hours of the measurement, indicating that conductivity excursions are likely due to runoff events. In the case of Nuttree Branch, the antecedent precipitation event was light snow, so runoff of road salts and deicing fluids could be responsible for the conductivity excursions.

In addition to the impaired benthic stations, conductivity data from 43 other stations within the impaired watersheds were analyzed. Of those, all but one station had average conductivity levels in the no to low probability range for stressor effects. The average conductivity in an upstream Rohoic Creek station (2-RHC002.23) was 459 uS/cm and in the medium probability range for stressor effects.

In addition to periodic conductivity measurements, JMU collected diurnal conductivity data at each of the primary benthic stations during the summer of 2020. Diurnal data were collected at 15-minute intervals for 1 week at each station. Conductivity data during diurnal deployments are shown in Figure 26. At all stations, conductivity levels remained within the no to low probability range throughout the diurnal monitoring. At each site, conductivity levels decreased during storm events and then rebounded gradually afterwards. This was least evident in Swift Creek, where the upstream impoundments dampen the effects of storm events.

Total dissolved solids (TDS) are closely tied to conductivity, since it is the dissolved ions that transmit electrical current. Like conductivity, TDS levels were relatively low in all James River Tributaries Project streams (Figure 27). TDS averaged from 73 mg/L in Proctors Creek to 182 mg/L in Rohoic Creek. While all stations were statistically higher than the reference, mean and median TDS levels were within the no to low probability range for stressor effects. This indicates that TDS and conductivity are likely not stressors in these streams. Pond (2004) showed that on surface mined lands *Ephemeroptera* taxa decreased significantly at conductivity levels much above 500 uS/cm. Only two of the 365 conductivity values measured at benthic stations exceeded this threshold (1127 uS/cm in Nuttree Branch on 2/4/2019 and 640 uS/cm in Rohoic Creek on 11/18/2010).

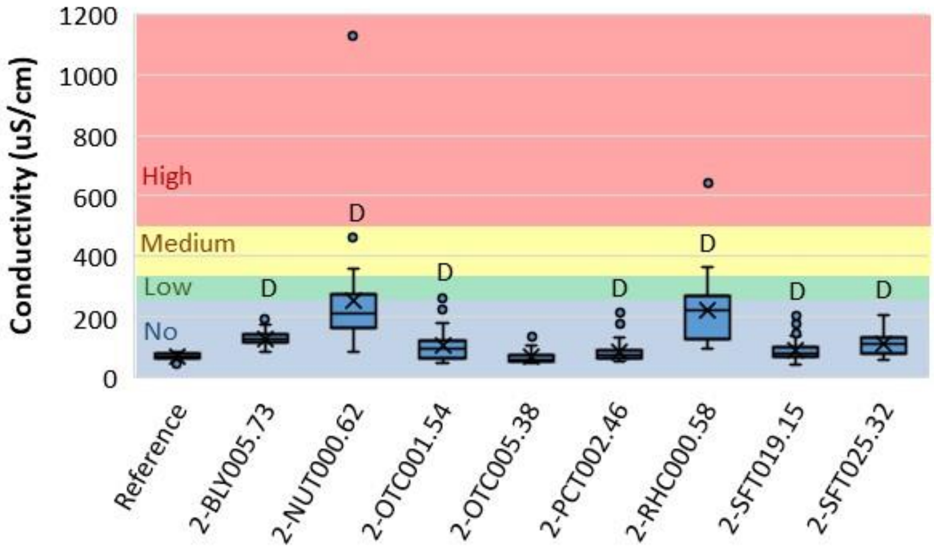

Figure 25. Conductivity in James River Tributaries Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represent the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the reference station. Colors represent the probability that data within that range would be responsible for causing stress.

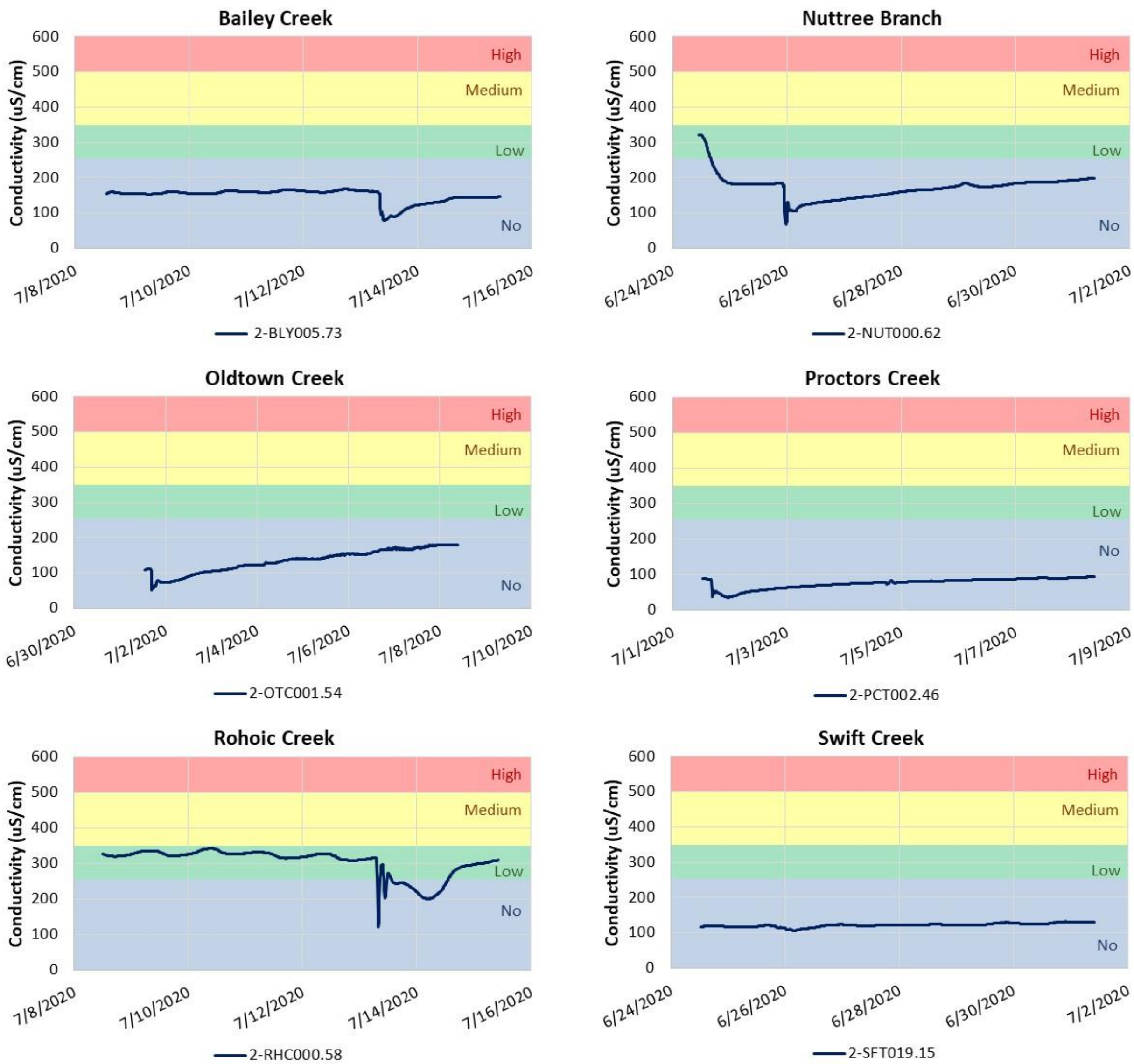

Figure 26. Diurnal conductivity conditions in James River Tributaries Project streams. Colors represent the probability that data within that range would be responsible for causing stress.

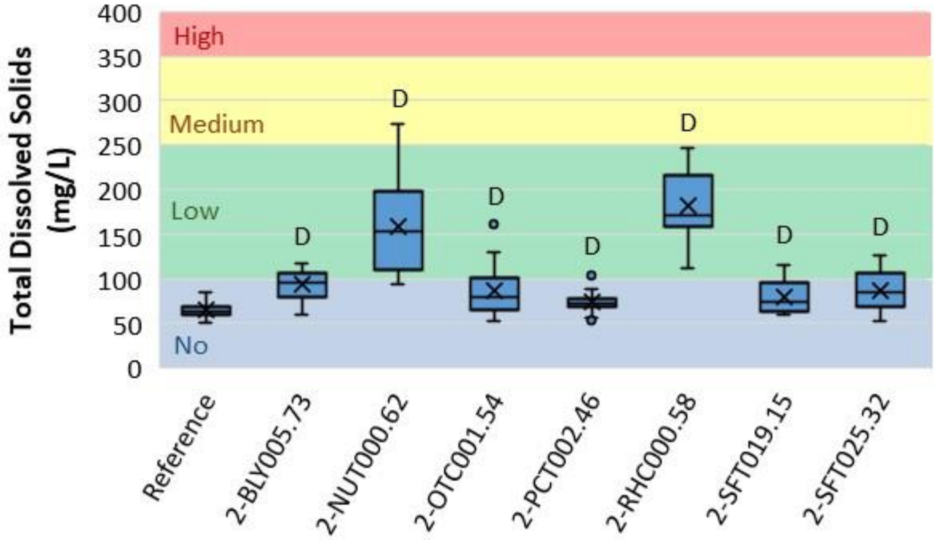

Figure 27. Total dissolved solids in James River Tributaries Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represent the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the reference station. Colors represent the probability that data within that range would be responsible for causing stress.

2.4.5. Dissolved Ions

Dissolved sodium, potassium, chloride, and sulfate were measured in James River Tributaries Project streams. Figure 28 shows the concentrations of these dissolved ions in comparison to the reference site and in comparison to VDEQ's stressor thresholds. Dissolved sodium concentrations in all streams were statistically higher than in the reference ($p<0.05$ in t-test with unequal variances), but levels in some streams were much higher than in others. Dissolved sodium levels averaged from 9.27 mg/L in Swift Creek to 20.5 mg/L in Nuttree Branch. Averages in Swift Creek were in the low probability range for stressor effects, while averages in Nuttree Branch were in the high probability range for stressor effects. All other streams averaged in the medium probability range for stressor effects.

Dissolved potassium concentrations in all streams except for Proctors Creek were statistically higher than in the reference ($p<0.05$ in t-test with unequal variances). Potassium levels averaged from 2.21 mg/L in Proctors Creek to 4.65 mg/L in Rohoic Creek. Averages in all streams (including the reference) were within the medium probability range for stressor effects, and no values were in the high probability range.

Dissolved chloride concentrations in all streams were statistically higher than in the reference ($p<0.05$ in t-test with unequal variances). Chloride levels averaged from 11.0 mg/L in Swift Creek to 54.3 mg/L in Rohoic Creek. Averages in Bailey Creek, Oldtown Creek, Proctors Creek, and Swift Creek were in the low probability range for stressor effects, while Nuttree Branch averaged in the medium probability range and Rohoic Creek averaged in the high probability range for stressor effects.

Dissolved sulfate concentrations in all streams except for Bailey Creek were statistically higher than in the reference ($p<0.05$ in t-test with unequal variances). Sulfate levels averaged from 5.47 mg/L in Swift Creek to 24.9 mg/L in Nuttree Branch. Averages in all streams were in the no to low probability range for stressor effects. It should be noted that one sulfate result in Bailey Creek (discarded as an outlier and not shown in Figure 28) was extremely high, measuring 233 mg/L. All other sulfate measurements in Bailey Creek were below 13 mg/L and averaged 7.90 mg/L, so this value was very anomalous. Flow gages from other nearby streams do not show storm conditions on this day, and no Pollution Response Program reports of spills or illicit discharges were reported on this day. While the source of this particularly high sulfate excursion is unknown, it appears to be isolated.

In summary, the potentially toxic ions chloride, potassium, sodium, and sulfate are not likely to be stressors in Bailey Creek, Oldtown Creek, Proctors Creek, or Swift Creek. In Nuttree Branch, sodium levels averaged in the high probability range for stressor effects, which could indicate a potential stressor. However, sodium is considered to be the least toxic of the major ions and Mount *et al.* (2016) found that sodium was typically only toxic to freshwater invertebrates at concentrations of 20-40 mM (or 460-920 mg/L Na). This is orders of magnitude above the sodium concentrations found in Nuttree Branch. Sodium may be a minor stressor in Nuttree Branch, but it is not likely responsible for the observed impairment. Similarly, chloride levels in Rohoic Creek averaged in the high probability range for stressor effects, but these levels are also far below levels of toxic concern. Virginia's water quality standard for chloride is 230 mg/L, which is approximately three times higher than the highest chloride concentration measured in Rohoic Creek. All samples were below toxic levels of potassium (78-390 mg/L) and sulfate (96-2400 mg/L) reported by Mount *et al.* (2016).

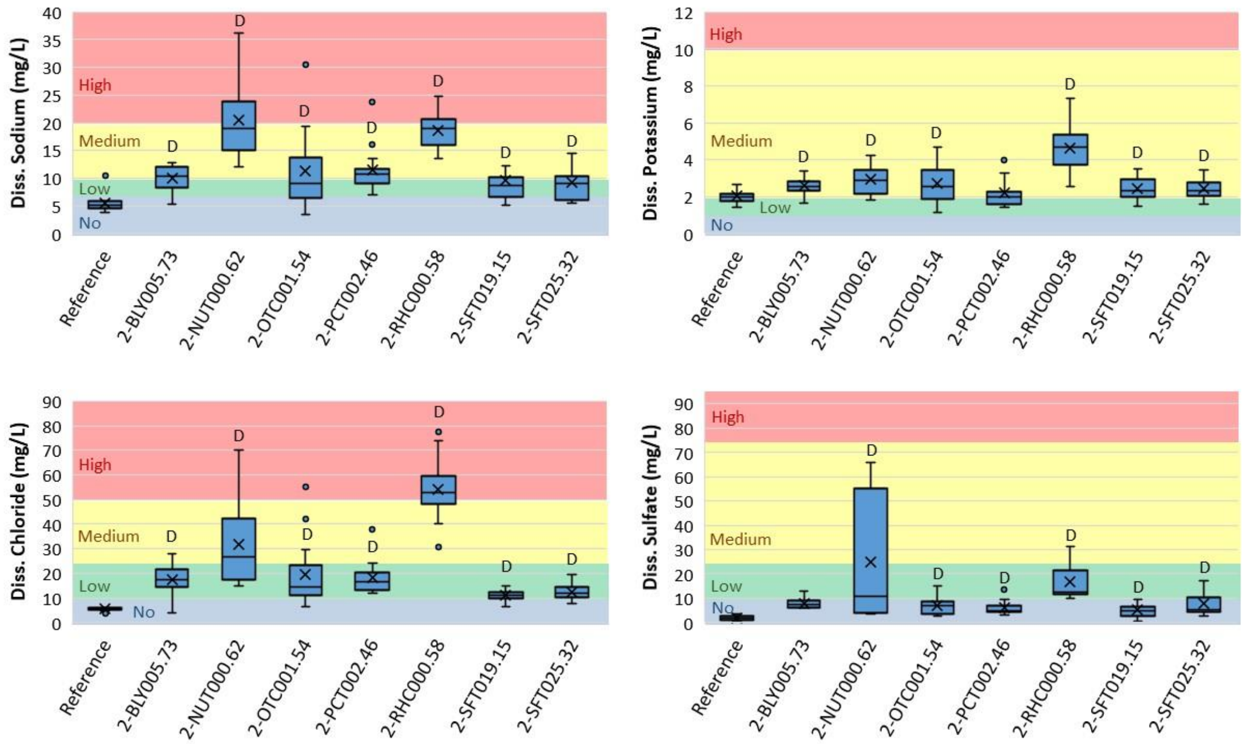

Figure 28. Dissolved ions in James River Tributaries Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represent the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the reference station. Colors represent the probability that data within that range would be responsible for causing stress.

2.4.6. Solids

Figure 29 shows total suspended solids (TSS) measured in James River Tributaries Project streams. Concentrations ranged from the detection limit of 3 mg/L to 50 mg/L in Swift Creek (2-SFT012.84). Average TSS values ranged from 6 mg/L in Proctors Creek and Swift Creek to 11 mg/L in Bailey Creek and Oldtown Creek. TSS was 18 mg/L in Nuttree Branch, but only a single TSS data point was collected. TSS data were not available for the reference stream (Jones Creek), so TSS concentrations at impaired stations were statistically compared to values at Swift Creek station 2-SFT012.84, where the benthic community is healthy and unimpaired. None of the streams were statistically different (p-value <0.05 in t-test with unequal variances) from station 2-SFT012.84 in TSS.

Figure 30 shows turbidity levels in James River Tributaries Project streams. Average turbidity levels ranged from 7.5 NTU at Swift Creek station 2-SFT019.15 to 13 NTU at Swift Creek station 2-SFT012.84. Turbidity was 25 NTU in Nuttree Branch, but only a single turbidity data point was collected. Turbidity data were not available for Bailey Creek. Turbidity data were also not available for the reference stream (Jones Creek), so turbidity levels at impaired stations were statistically compared to values at Swift Creek station 2-SFT012.84, where the benthic community is healthy and unimpaired. None of the streams were statistically different (p-value <0.05 in t-test with unequal variances) from station 2-SFT012.84 in turbidity.

In addition to periodic TSS and turbidity measurements, JMU collected diurnal turbidity data at each of the primary benthic stations during the summer of 2020. Diurnal data were collected at 15-minute intervals for 1 week at each station. During the diurnal deployment, each stream experienced a single storm event where turbidity peaked (Figure 31). Based on the intensity of the storm and the characteristics of the watershed, each stream experienced differing turbidity conditions. Turbidity peaks of 207, 347, 91, 396, 42, and 25 NTU were observed in Bailey Creek, Nuttree Branch, Oldtown Creek, Proctors Creek, Rohoic Creek, and Swift Creek, respectively. This indicates that even relatively small storm events can produce very high levels of suspended solids in Bailey Creek, Nuttree Branch, and Proctors Creek.

In summary, suspended solids may be a stressor in Bailey Creek, Nuttree Branch, and Proctors Creek, where diurnal monitoring showed very high turbidity during small storm events. Total suspended solids and turbidity were also higher in Nuttree Branch than the unimpaired Swift Creek station, but this represented only a single sample. The remaining stations (Oldtown Creek, Rohoic Creek, and Swift Creek) were relatively similar to the unimpaired Swift Creek station in TSS and turbidity levels, and turbidity levels during diurnal monitoring were moderate.

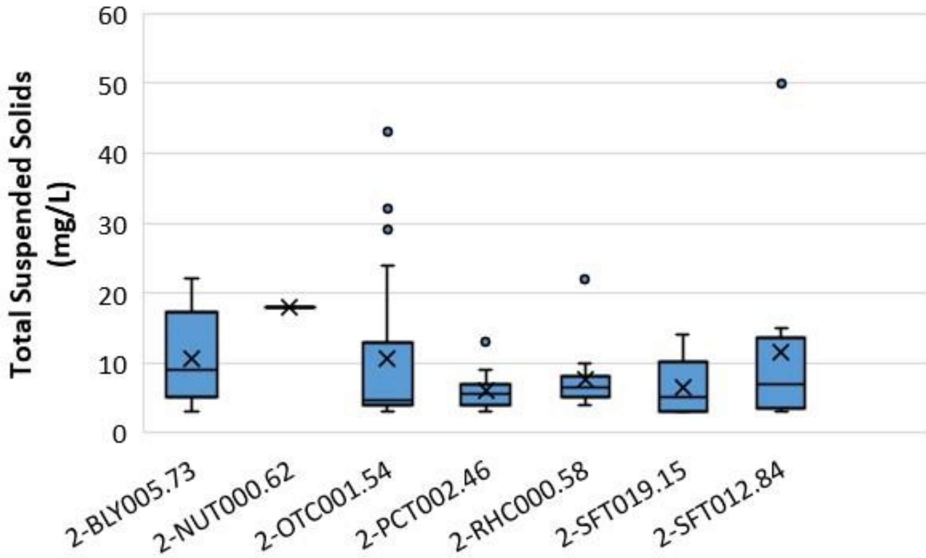

Figure 29. Total suspended solids in James River Tributaries Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represent the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean.

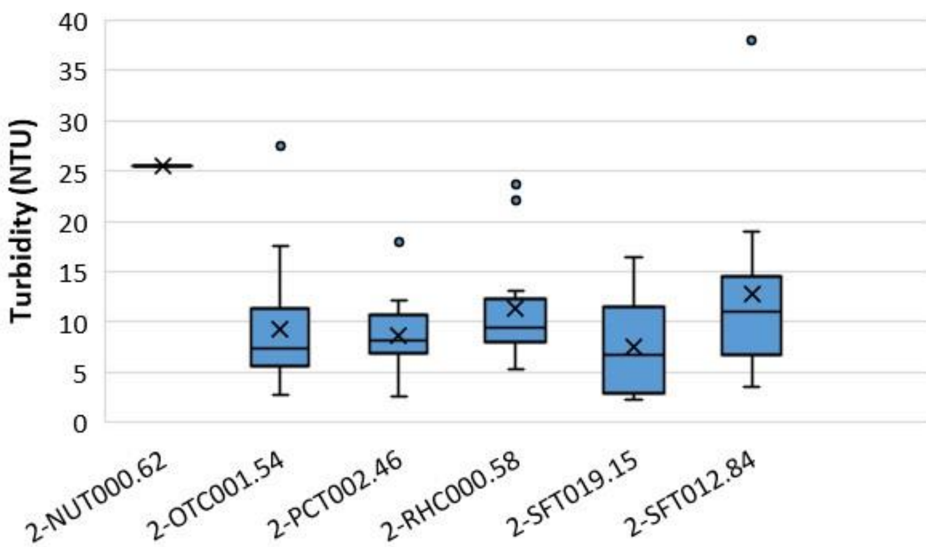

Figure 30. Turbidity in James River Tributaries Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represent the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean.

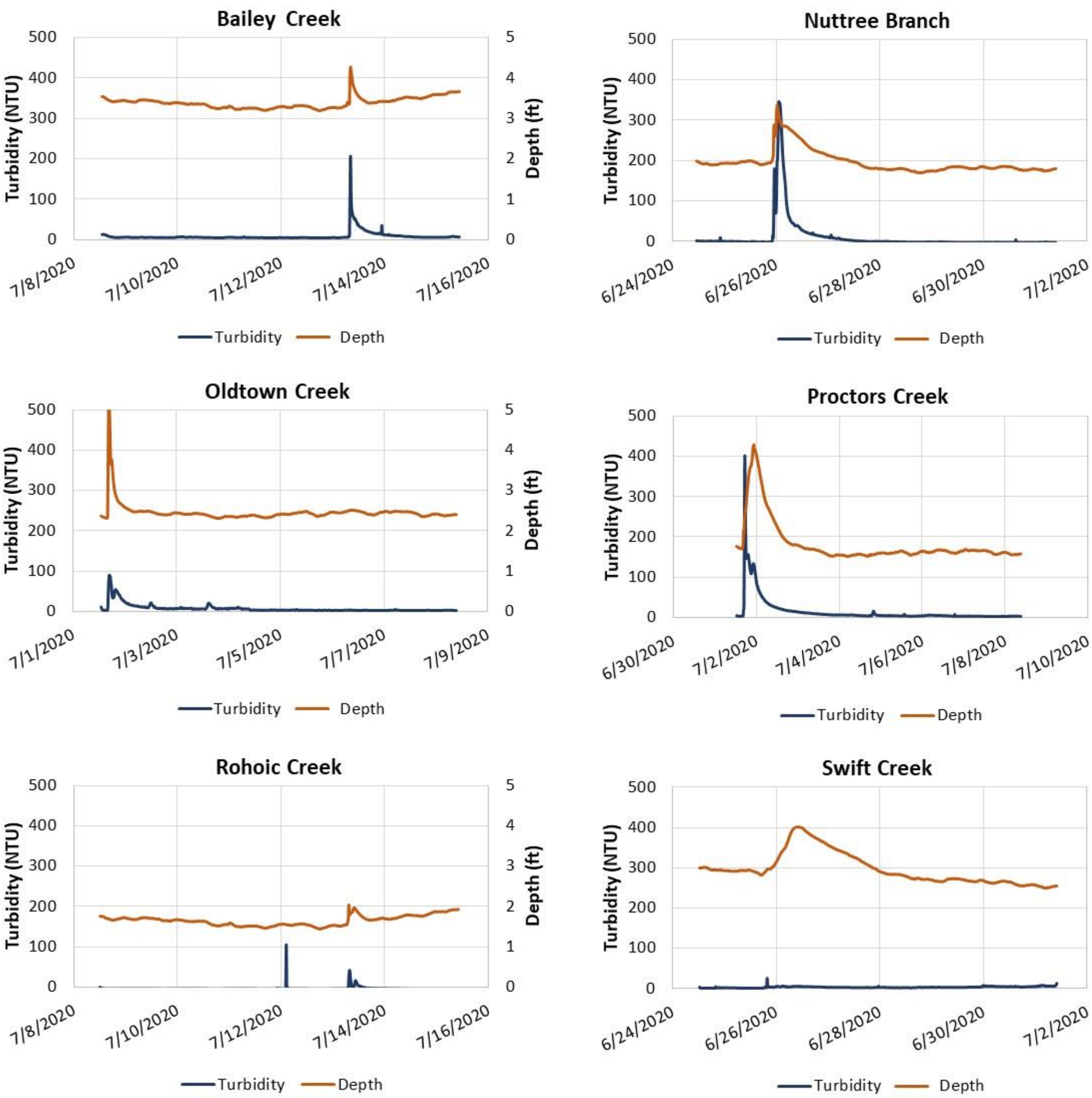

Figure 31. Diurnal turbidity conditions and depth of flow in James River Tributaries Project streams.

2.4.7. Organic Matter

Various forms of organic matter were measured in James River Tributaries Project streams. The measurement of total volatile solids (TVS) captures the mass of suspended or dissolved solids in the stream that volatilizes when heated to 550ºC. At this temperature, only inorganic material remains, so TVS represents the organic fraction. TVS levels in James River Tributaries Project streams are shown in Figure 32. TVS ranged from 6 mg/L in the unimpaired section of Swift Creek

(2-SFT004.92) to 102 mg/L in Bailey Creek. Only one TVS value was available from the reference stream (Jones Creek), so TVS concentrations at impaired stations were statistically compared to values at Swift Creek station 2-SFT004.92, where the benthic community is healthy and unimpaired. TVS concentrations averaged 19 mg/L at this Swift Creek station and were statistically significantly higher in Bailey Creek and Oldtown Creek, where values averaged 44 and 33 mg/L, respectively. TVS concentrations were also relatively high in Nuttree Branch (36 mg/L) and Rohoic Creek (99 mg/L), but statistical comparison was not possible for these streams due to low sample numbers.

Total organic carbon (TOC) was also measured in James River Tributaries Project streams. TOC is the mass of carbon in organic form dissolved or suspended in the water column. TOC levels in James River Tributaries Project streams are shown in Figure 33. TOC ranged from 2.2 mg/L in the unimpaired reference to 11.9 mg/L in Oldtown Creek and Proctors Creek. Only one TOC value was available from the reference stream (Jones Creek), so TOC concentrations at impaired stations were statistically compared to values at Swift Creek station 2-SFT005.57, where the benthic community is healthy and unimpaired. TOC concentrations averaged 6.8 mg/L at this Swift Creek station, and no stations were statistically higher, although comparisons could not be made for Nuttree Branch, Oldtown Creek, Proctors Creek, or Rohoic Creek due to low sample numbers.

In general, total volatile solids and total organic carbon were relatively high for all of the impaired streams, with the exception of Swift Creek. Fractions of total organic carbon in the dissolved form were also relatively high. For stations that had total and dissolved organic carbon (DOC) measurements, the average percentage of TOC in the dissolved form was 75%. This means that high TOC concentrations of 11.9 mg/L would translate to 9 mg/L of dissolved organic carbon. In a survey of eastern streams, Kaufmann *et al.* (1991) found that only two regions (Florida and the Mid-Atlantic coastal plain) exceeded a median DOC of 2 mg/L. The James River Tributaries Project streams are located in this Mid-Atlantic coastal plain region, where DOC is naturally higher, but levels observed in at least the two highest streams (Oldtown Creek and Proctors Creek) are near the upper 80th percentile of streams within this Mid-Atlantic coastal plain region.

In the Mid-Atlantic coastal plain region, stream slopes are very shallow and hydrologically connected wetlands are common. In these low-lying areas, organic matter from growing or dead vegetation accumulates in rich wetland soils. When flooded and hydrologically connected to larger drainage networks, these wetland areas feed high levels of organic matter to downstream creeks. These streams exhibit high levels of organic carbon (measured as either TVS or TOC), particularly in the dissolved phase (DOC). This labile organic matter represents a readily available food source for heterotrophic microbes, and when degraded, oxygen is consumed, potentially causing decreases in in-stream dissolved oxygen. Streams in this region that exhibit these conditions are characterized by shallow slopes, sandy substrate, dark discolored water (blackwater), and low dissolved oxygen. This condition is naturally occurring in blackwater swamps and blackwater creeks but may also be exacerbated by anthropogenic inputs of nutrients, which fuel algal growth and further decrease oxygen levels. Oldtown Creek and Proctors Creek appear to at least in part exhibit these blackwater conditions.

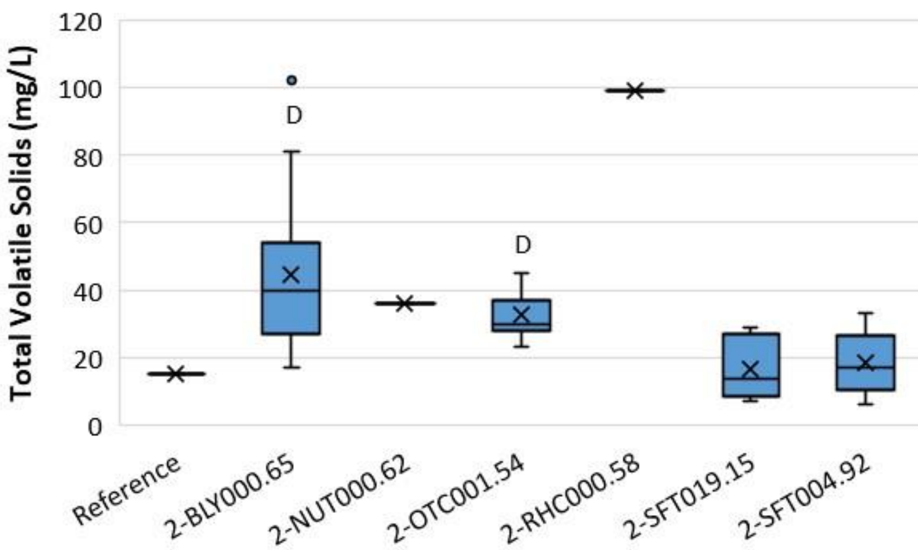

Figure 32. Total volatile solids in James River Tributaries Project streams. The "D" indicates a statistically significant difference from unimpaired station 2-SFT004.92.

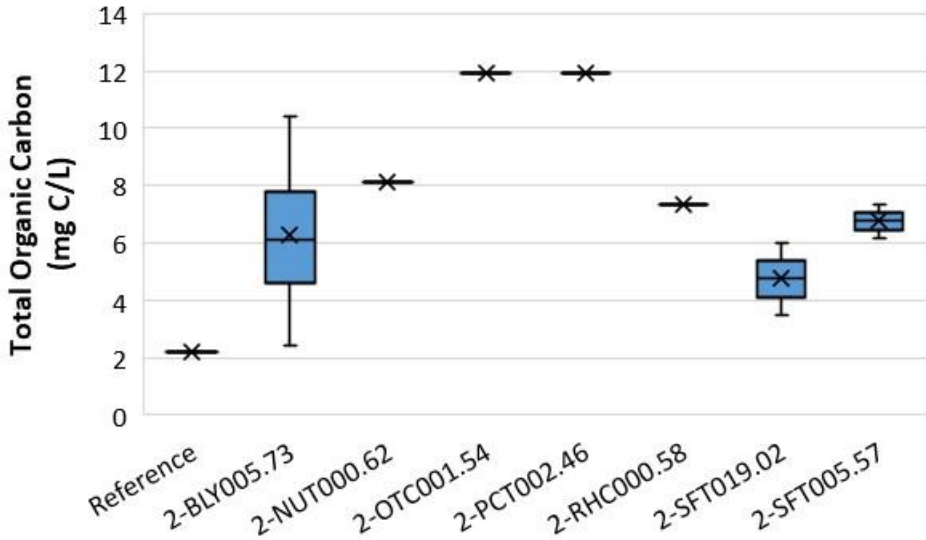

Figure 33. Total organic carbon in James River Tributaries Project streams.

2.4.8. Nutrients - Phosphorus

Nitrogen and phosphorus are the primary nutrients of concern in freshwater. These nutrients are necessary to support healthy ecosystems, but excess nutrients can lead to eutrophication. Excess nutrients spur algae growth and can change the benthic community composition. An overabundance of algae can reduce oxygen levels, leading to further changes in community composition and eventually hypoxic conditions. The initiation of this eutrophication process is not reliant upon the total nutrient availability, but upon the availability of the limiting nutrient. The typical ratio of nitrogen to phosphorus in algae is 7.5:1, so ratios above 7.5 indicate that phosphorus is the limiting nutrient and ratios below 7.5 indicate that nitrogen is the limiting nutrient. In the James River Tributaries Project streams, the average nitrogen to phosphorus ratio ranges from 10 to 17, indicating that phosphorus is the limiting nutrient.

Over time, VDEQ has measured various forms of phosphorus (total and dissolved orthophosphate, and total and dissolved phosphorus). While these various forms signal the availability of nutrients for biological uptake, total phosphorus is used in the stressor analysis to identify the potential for nutrient enrichment. Figure 34 shows the total phosphorus levels in James River Tributaries Project streams. Total phosphorus averaged from 0.045 mg/L in Swift Creek to 0.090 mg/L in Rohoic Creek. None of the stations had statistically higher total phosphorus levels than the reference site, however, this was strongly influenced by high variability in the reference site. One outlier value of 0.7 mg/L was observed in the reference station. This value and other outliers in Proctors Creek (0.45 mg/L) and Rohoic Creek (0.52 mg/L) are not shown on Figure 34 in order to focus the scale on the region of interest. If those outliers were removed from the statistical analysis then all stations would be declared as statistically higher than the reference (t-test with unequal variances and alpha = 0.05).

While VDEQ does not have nutrient criteria for freshwater streams, USEPA has published recommended criteria by ecoregion (USEPA, 2000a). Nuttree Branch and the majority of Swift Creek are in the Piedmont Level 3 Ecoregion, and the remaining impaired watersheds are in the Southeastern Plains Level 3 Ecoregion (Figure 35). Based on these ecoregion designations, the recommended total phosphorus criterion based on the 25th percentile of streams is 0.03 mg/L for the Piedmont and 0.0225 mg/L for the Southeastern Plains. All of the impaired streams exceeded this recommended criterion, while the reference station did not.

Median total phosphorus levels were in the low probability range for stressor effects in Bailey Creek, Nuttree Branch, Proctors Creek, and Swift Creek (2-SFT025.32). Medians were in the medium probability range in Oldtown Creek and Rohoic Creek. Figure 36 shows the time series of total phosphorus levels in each stream. All streams (except for Nuttree Branch) had individual samples above 0.1 mg/L total phosphorus and in the high probability range for stressor effects. These excursions were much more prevalent in Oldtown Creek and Rohoic Creek than the other streams. Excursions above 0.1 mg/L represented 14% of samples in Oldtown Creek and 27% of samples in Rohoic Creek. All other streams had total phosphorus excursions above 0.1 mg/L less than 5% of the time. In these streams, excursions occasionally occurred during spring or summer months, but in Oldtown Creek and Rohoic Creek, excursions occurred each year and were more sustained during spring and summer months.

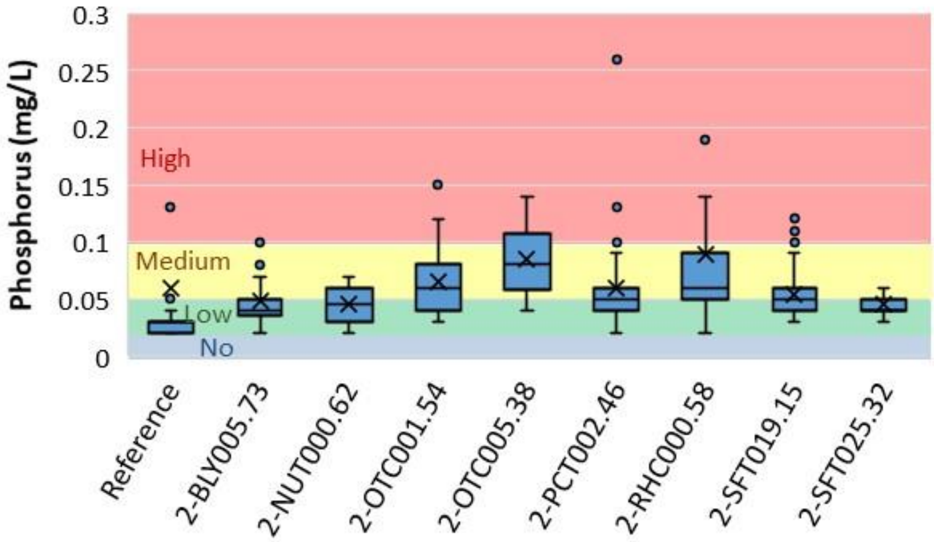

Figure 34. Total phosphorus in James River Tributaries Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represent the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. Colors represent the probability that data within that range would be responsible for causing stress.

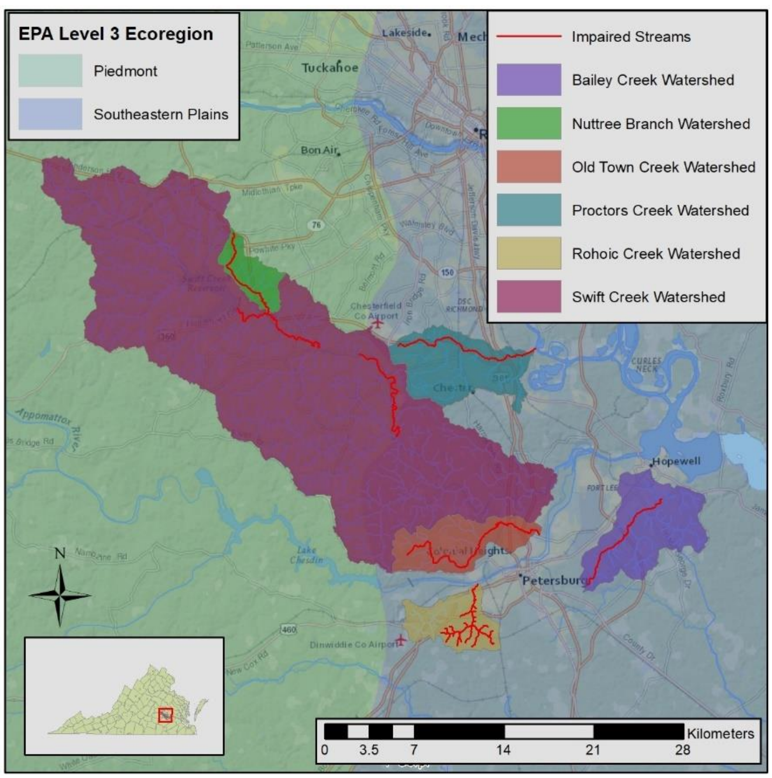

Figure 35. Location of impaired watersheds within EPA Level 3 Ecoregions.

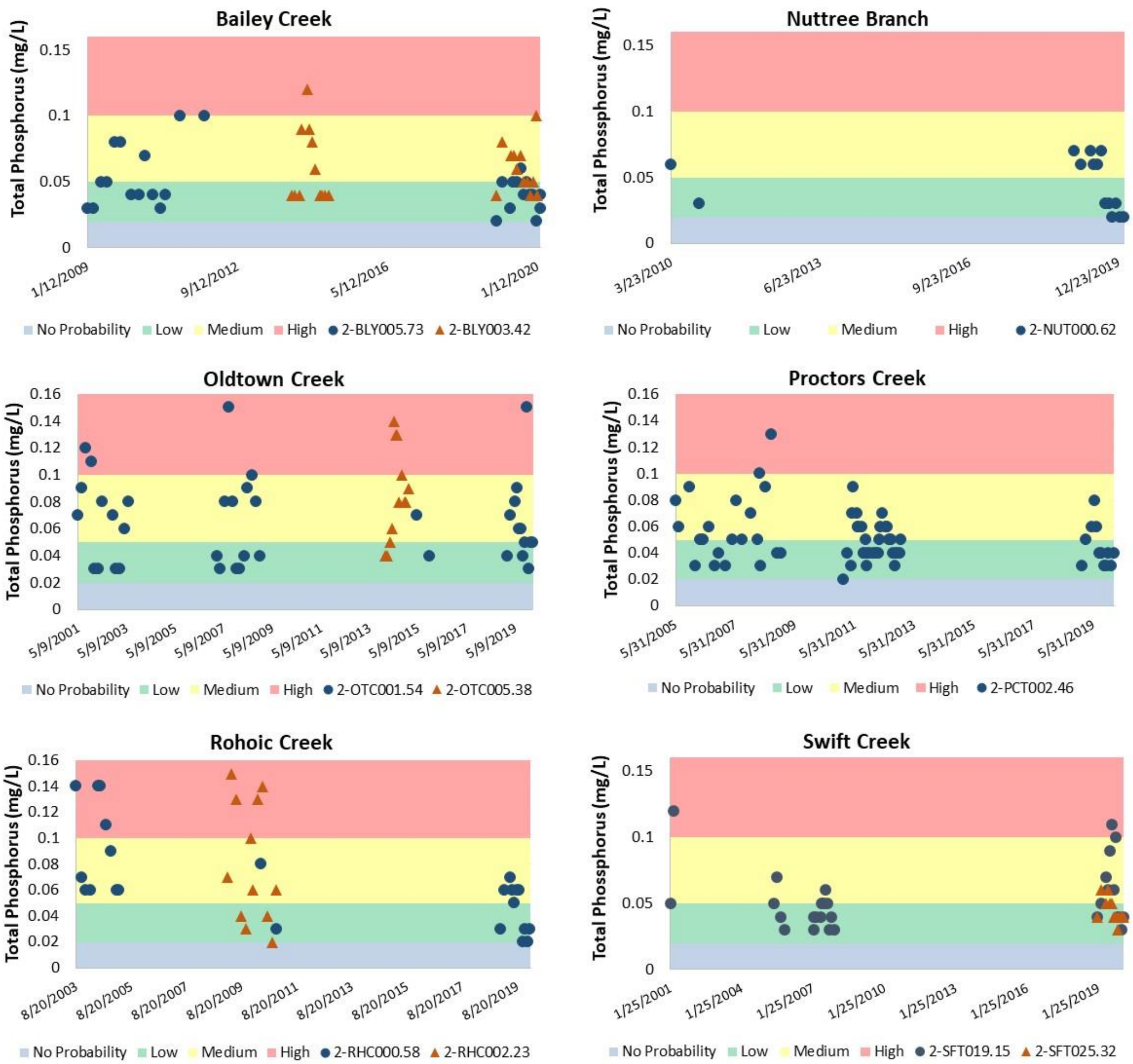

Figure 36. Total phosphorus over time in James River Tributaries Project streams. Colors represent the probability that data within that range would be responsible for causing stress.

2.4.9. Nutrients - Nitrogen

Over time, VDEQ has measured various forms of nitrogen (total and dissolved nitrite, total and dissolved nitrate, total and dissolved ammonia, total Kjeldahl nitrogen, and total nitrogen). While these various forms signal the availability of nutrients for biological uptake, total nitrogen is used in the stressor analysis to identify the potential for nutrient enrichment. Figure 37 shows the total nitrogen levels in James River Tributaries Project streams. Total nitrogen averaged from 0.56 mg/L in Swift Creek to 0.96 mg/L in Proctors Creek. None of the streams were statistically higher in total nitrogen than the reference (t-test with unequal variance and alpha = 0.05). In fact, Proctors Creek and Rohoic Creek were only slightly higher in total nitrogen (0.96 and 0.93 mg/L, respectively) than the reference (0.92 mg/L), and all other streams were lower than the reference. The mean and median total nitrogen level in all streams were in the low probability range for stressor effects, meaning that nitrogen is unlikely to be a stressor in any of the James River Tributaries Project streams. In addition, nitrogen to phosphorus ratios indicate that nitrogen is not the limiting nutrient in these streams, so controlling nitrogen would have little effect on reducing nutrient enrichment.

While VDEQ does not have nutrient criteria for freshwater streams, USEPA has published recommended criteria by ecoregion (USEPA, 2000a). Nuttree Branch and the majority of Swift Creek are in the Piedmont Level 3 Ecoregion, and the remaining impaired watersheds are in the Southeastern Plains Level 3 Ecoregion (Figure 35). The recommended total nitrogen criterion based on the 25th percentile of streams is 0.615 mg/L for the Piedmont (which includes Nuttree Branch and Swift Creek) and 0.618 mg/L for the Southeastern Plains (which includes the remainder of the James River Tributaries Project streams). Median total nitrogen levels in Bailey Creek and Swift Creek (2-SFT025.32) met this criterion, while the remainder of the streams (including the reference) slightly exceeded it.

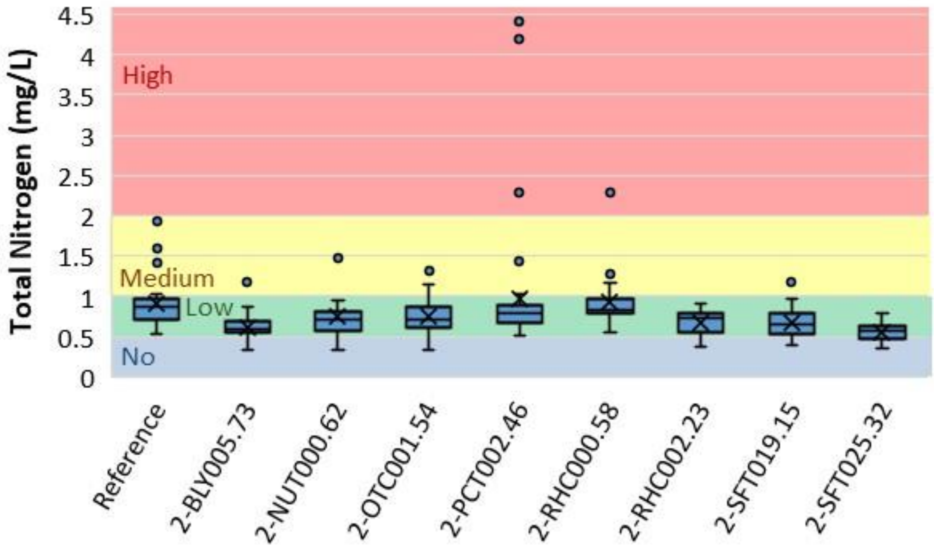

Figure 37. Total nitrogen in James River Tributaries Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represent the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. Colors represent the probability that data within that range would be responsible for causing stress.

2.4.10. Ammonia

Ammonia is a reduced form of nitrogen that can be toxic at certain temperatures and pHs. Figure 38 shows the ammonia levels in each of the streams along with the relevant water quality standards. The water quality standard for ammonia is dependent upon pH and temperature, so it varies with each sample. None of the samples at any of the stations had ammonia levels above or even close to the water quality standard. Ammonia levels averaged from the detection limit of 0.04 mg/L in Rohoic Creek to 0.11 mg/L in Oldtown Creek. Only one ammonia result was available from the reference site (at the detection limit of 0.04 mg/L), so no comparisons could be made between impaired streams and the reference site. The maximum observed ammonia level was 0.54 mg/L in Oldtown Creek. Even at this maximum level, it was well below the calculated chronic water quality criterion of 3.84 mg/L. For this reason, ammonia is not likely a stressor in any of the James River Tributaries Project streams.

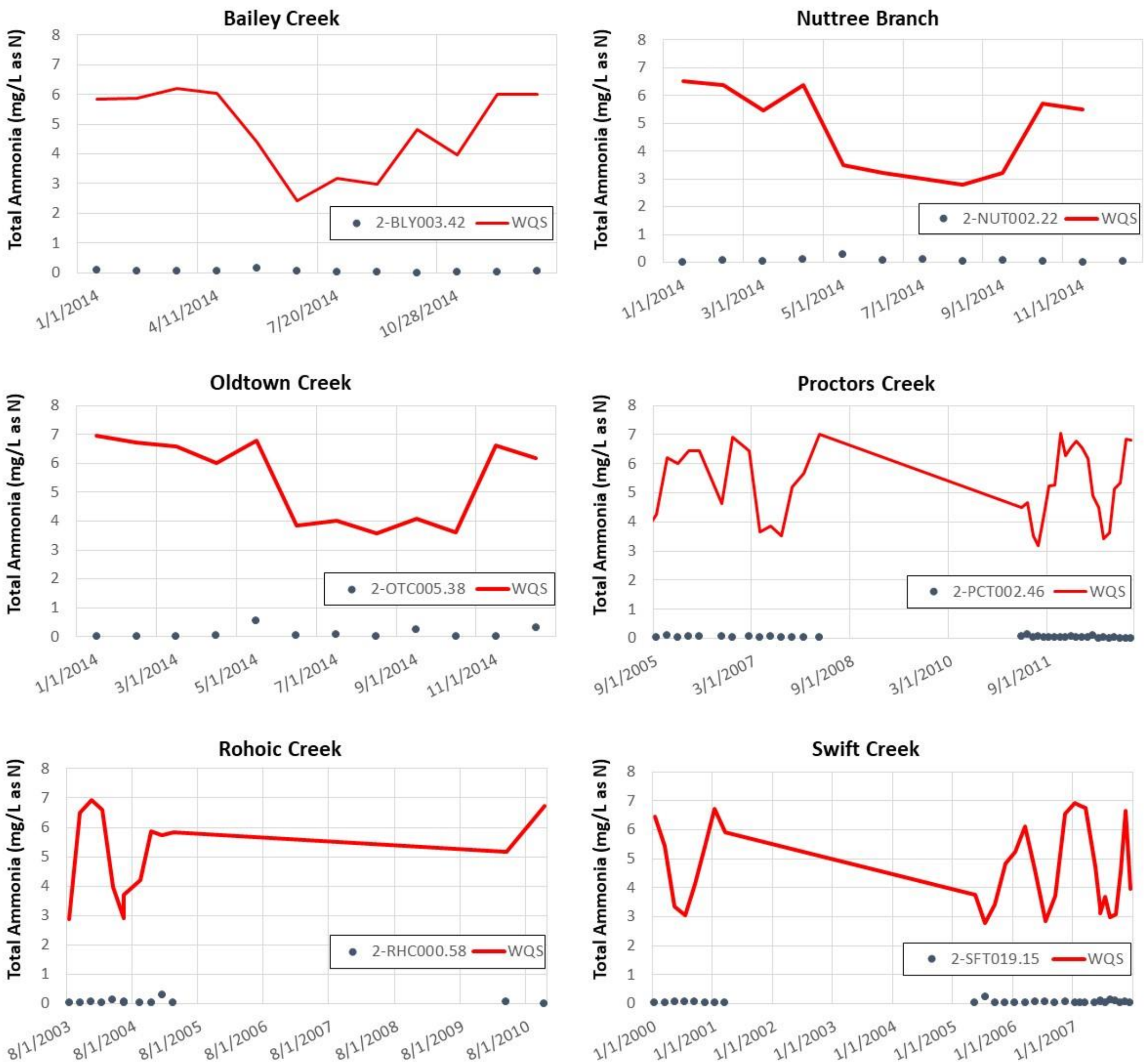

Figure 38. Ammonia levels in James River Tributaries Project streams.

2.4.11. Dissolved Metals

Dissolved metals were measured in each of the James River Tributaries Project streams on at least one occasion. Metals were sampled twice in Nuttree Branch, eight times in Rohoic Creek, and four times in Swift Creek. Table 13 shows the range and average values of eight metals in each stream along with the associated water quality standard (9VAC25-260-140). Virginia's water quality standards for dissolved metals depends upon the hardness of the water (except for arsenic and selenium), so standards were calculated specifically for each stream based on hardness values measured at the time of sampling. All average dissolved metals concentrations were below the respective water quality standards, indicating that these metals do not pose a risk to aquatic life. However, one individual sample in Rohoic Creek exceeded the chronic water quality criterion for selenium of 5 ug/L. A selenium concentration of 6.2 ug/L was measured on 7/28/10 at station 2-RHC002.23. This indicates that selenium could be a possible stressor in Rohoic Creek, however, seven other samples from this stream were all below 4.02 ug/L.

For toxic metals that do not have chronic water quality criteria for aquatic life use in Virginia (aluminum, antimony, barium, beryllium, silver, and thallium), toxicity reference values (TRVs) were obtained from the literature. TRVs are threshold values below which toxic freshwater effects are not expected. Table 14 shows the range and average values of these six metals in each stream along with the associated TRVs. None of the streams exceeded TRVs in any of the samples, indicating that these metals are not expected to pose a risk to aquatic life.

To investigate the combined effects of dissolved metals, a criterion unit was calculated for each sample as the ratio of measured values to the chronic water quality criterion. In cases where the measured value was censored at the detection limit, half the detection limit was used for the criterion unit calculation. The criterion unit values for each of the eight metals subject to Virginia water quality standards were then summed to obtain a cumulative criterion unit (CCU) for each sampling event. The cumulative criterion unit represents the additive effect of the metals in total. A value greater than one indicates that the combined effects of the metals acting additively could be toxic. The CCUs ranged from 0.49 in Swift Creek to 1.38 in Rohoic Creek (Table 15). For the highest value in Rohoic Creek, selenium represented 90% of the CCU. The CCU values calculated for the James River Tributaries Project streams fall into the range of no probability to low probability of causing stressor effects, according to VDEQ’s stressor threshold analysis (VDEQ, 2017).

To investigate the combined effects of dissolved metals that do not have chronic water quality criteria for aquatic life in Virginia, a toxicity reference value (TRV) quotient was calculated for each sample as the ratio of measured values to the literature-based TRV. In cases where the measured value was censored at the detection limit, half the detection limit was used for the TRV quotient. The TRV quotient values for each of the six metals were then summed to obtain a TRV index for each sampling event. The TRV index is similar to the CCU and represents the additive effect of the metals in total. A value greater than one indicates that the combined effects of the metals acting additively could be toxic. The TRV index values ranged from 0.14 in Nuttree Branch to 0.74 in Swift Creek (Table 15). All of the TRV index values were below 1.0, indicating that these six dissolved metals are not likely a stressor to the benthic community.

Based on comparison to individual water quality standards, literature-based toxicity reference values, cumulative criterion units, and TRV indices, dissolved metals are not likely a stressor in the James River Tributaries Project streams, with the exception of selenium in Rohoic Creek. One sample in Rohoic Creek exceeded the water quality standard for selenium, but average selenium values were below the standard.

Table 13. Average dissolved metals concentrations and corresponding water quality standards for James River Tributaries Project streams.

Metal	Water Quality Standard[1] (ug/L)	Average (Range)[2] in ug/L					
		Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek
Arsenic	150	0.1	0.44 (0.32-0.56)	0.62	0.57	1.0 (0.55-1.6)	0.3 (0.25-0.34)
Cadmium	0.55 (0.25-1.2)	0.05	0.048 (0.045-0.05)	0.05	0.05	0.049 (0.01-0.75)	0.05 (0.005-0.05)
Chromium	56 (24-130)	0.44	0.61 (0.36-0.85)	0.44	0.44	0.7 (0.36-0.97)	0.42 (0.38-0.46)
Copper	6.7 (2.7-15)	0.48	1.5 (1.1-1.9)	1	0.98	0.75 (0.45-1.2)	0.91 (0.80-1)
Lead	7.9 (2.3-21)	0.05	0.17 (0.05-0.28)	0.62	0.64	0.11 (0.005-0.28)	0.088 (0.05-0.2)
Nickel	15 (6.3-35)	1.9	0.87 (0.52-1.2)	0.89	0.94	2 (1.1-2.7)	0.39 (0.3-0.44)
Selenium	5	0.15	0.26 (0.15-0.37)	0.1	0.15	3.2 (1.7-**6.2**)	0.23 (0.15-0.25)
Zinc	89 (36-200)	9.2	3.1 (1.6-4.5)	5	5.1	8.6 (4.1-15)	0.88 (0.5-1.4)

[1] Water quality standards for all metals except for arsenic and selenium are hardness based, so standards varied with individual samples.
[2] Only one metals sample was available for Bailey Creek, Oldtown Creek, and Proctors Creek, so no range information is presented.
Bold values are above water quality standards.

Table 14. Average dissolved metals concentrations and corresponding toxicity reference values for James River Tributaries Project streams.

Metal	Toxicity Reference Value (ug/L)	Average (Range)[1] in ug/L					
		Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek
Aluminum[2]	490 (52-1200)	5.5	32 (9.9-55)	130	140	35 (6.9-84)	23 (9.4-56)
Antimony[3]	30	0.42	0.1 (0.09-0.12)	0.08	0.09	0.15 (0.0005-0.25)	0.2 (0.06-0.25)
Barium[4]	1700	59	39 (36-42)	37	30	110 (67-190)	33 (26-43)
Beryllium[5]	5.3	0.05	0.12 (0.05-0.18)	0.04	0.05	0.055 (0.031-0.1)	0.05 (0.05-0.05)
Silver[3]	0.12	0.01	0.0065 (0.003-0.01)	0.02	0.01	0.024 (0.002-0.05)	0.04 (0.01-0.05)
Thallium[3]	40	0.02	0.025 (0.05-0.045)	0.005	0.005	0.033 (0.0035-0.069)	0.039 (0.005-0.05)

[1] Only one metals sample was available for Bailey Creek, Oldtown Creek, and Proctors Creek, so no range information is presented for these streams.
[2] Toxicity reference value was based on pH, hardness, and dissolved organic carbon as specified in USEPA, 2018b.
[3] Toxicity reference value from USEPA, 1987.
[4] Toxicity reference value from Golding et al., 2018.
[5] Toxicity reference value from USEPA, 1980.

Table 15. Cumulative criterion units and toxicity reference value index scores for dissolved metals in James River Tributaries Project streams.

Watershed	Stream	Station	Date	CCU[1]	TRV Index[2]
Bailey Creek	Bailey Creek	2-BLY005.73	3/11/2020	0.71	0.15
Nuttree Branch	Nuttree Branch	2-NUT000.62	3/23/2010	1.30	0.27
			3/11/2020	0.50	0.14
Oldtown Creek	Oldtown Creek	2-OTC001.54	4/28/2015	1.16	0.60
Proctors Creek	Proctors Creek	2-PCT002.46	3/11/2020	1.17	0.24
Rohoic Creek	Rohoic Creek	2-RHC000.58	4/27/2010	1.27	0.14
			3/11/2020	0.67	0.19
		2-RHC002.23	2/12/2009	0.63	0.56
			6/11/2009	0.76	0.54
			10/7/2009	0.87	0.55
			12/16/2009	0.89	0.41
			3/16/2010	1.19	0.24
			7/28/2010	1.38	0.16
Swift Creek	Swift Creek	2-SFT004.80	3/8/2007	0.72	0.68
		2-SFT019.02	3/25/2008	0.68	0.74
			4/28/2009	0.74	0.50
		2-SFT025.32	3/10/2020	0.49	0.15

[1] Cumulative criterion unit (CCU) is the sum of the dissolved metal concentration to water quality standard ratio for each metal. Values in blue are in the no probability range of stressor effects, and values in green are in the low probability range of stressor effects.
[2] Toxicity reference value (TRV) index is the sum of the dissolved metal concentration to toxic threshold value ratio for each metal.

2.4.12. Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs are a class of chemicals that occur naturally in coal, oil, and gasoline and can be generated when organic fuels are burned. PAHs in the aquatic environment are commonly associated with oil or fuel leaks or spills, but PAHs can also be elevated in urban areas from the runoff of deposited fossil fuel combustion byproducts. Many PAH compounds are toxic and can adversely impact benthic aquatic communities when they build up in sediments. Within the James River Tributaries Project streams, PAHs were only measured once in water in Swift Creek (7/15/2013) and once in sediment in Bailey Creek (5/29/01). In Swift Creek, the following 16 priority PAHs were measured in the water column: naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, benzo[g,h,i]perylene, indeno[1,2,3-c,d]pyrene, and dibenz[a,h]anthracene. All of these compounds were below the detection limit in the Swift Creek sample. In Bailey Creek, total PAHs and 24 individual PAHs were measured. None of the PAH compounds exceeded probable effect concentrations (MacDonald *et al.*, 2000). This is an indication that PAHs are not a stressor in Swift Creek or Bailey Creek. No data on PAHs were available for the other James River Tributaries Project streams. PAHs are not likely a stressor in Nuttree Branch, because high levels in that stream would have been captured in downstream Swift Creek sampling.

2.4.13. Sediment Toxics - PCBs

Polychlorinated biphenyls (PCBs) are a group of man-made chlorinated organic compounds that were widely used in electrical equipment and other applications from the 1930s to 1970s. While their manufacturing has been banned in the US for decades, these compounds are extremely persistent in the environment and can continue to produce toxicity in aquatic sediments. PCBs were analyzed in sediments collected from Bailey Creek, Oldtown Creek, Swift Creek, and two Swift Creek tributaries. Total PCB levels were below detection in each of the streams except for the tidal portion of Bailey Creek (2-BLY000.65), where levels were as high as 3500 ug/kg (Table 16). According to MacDonald *et al.* (2000), the probable effect concentration (PEC) for PCBs is 676 ug/kg, so levels at station 2-BLY000.65 in Bailey Creek are sufficient to cause toxicity to the benthic community. However, further analysis as part of the James River PCB TMDL has indicated that PCBs in Bailey Creek do not originate from upstream non-tidal areas. They likely originate from industrial facilities that drain to the tidal portion of the Bailey Creek or from the James River.

Bailey Creek also has a PCB fish consumption impairment due to fish samples from 2-BLY005.72 exceeding the human health screening level for PCBs in 1997. In 2003 and 2009, additional sampling of sediments and water for PCBs was conducted in the Bailey Creek watershed as part of the James River PCB TMDL. Results of these analyses are shown in Figure 39. In the water column, PCBs average 2729 pg/L at tidal station 2-BLY000.65, which exceeds the human health water quality standard of 640 pg/L by more than 4 times. However, upstream at stations 2-BLY003.42 and 2-BLY005.73, PCB levels averaged only 258 and 310 pg/L, respectively. Results of sediment sampling in tributaries and ditches leading to the tidal portion of Bailey Creek revealed that significant sources of PCBs are likely originating from the industrial area formerly owned by

Aqualon and currently owned by Ashland Specialty Ingredients (VPDES #VA0003492). This area is directly upstream from the 2-BLY000.65 station, but would not impact upstream non-tidal Bailey Creek monitoring stations.

In summary, PCBs are not a stressor in Oldtown Creek and Swift Creek. PCBs are not likely a stressor in Nuttree Branch, because fish tissue sampling in downstream areas have not identified problems. In the tidal portion of Bailey Creek (near 2-BLY000.65), PCBs are a human health concern for fish consumption. In the upper reaches of the stream (2-BLY005.73), however, some other stressor is likely responsible for the benthic impairment.

Table 16. Polychlorinated biphenyl (PCB) concentrations analyzed in sediments of James River Tributaries Project streams.

Watershed	Stream	Station	Date	Analysis Type	Concentration (ug/kg)[1]
Bailey Creek	Bailey Creek	2-BLY000.65	9/30/1980	Total PCBs	3500
		2-BLY000.65	9/17/1991	Total PCBs	2400
		2-BLY000.65	3/6/1997	Total PCBs	1640
		2-BLY000.65	11/26/2001	Total PCBs	<30
Oldtown Creek	Oldtown Creek	2-OTC001.54	11/26/2001	Total PCBs	<20
Swift Creek	Swift Creek	2-SFT022.14	10/25/2004	16 PCB congeners	<2.9
		2-SFT031.08	4/19/2001	Total PCBs	<10
		2-SFT033.42	6/18/2001	Total PCBs	<40
		2-SFT034.38	7/10/2001	Total PCBs	<20
		2-DYC000.19	5/7/2001	Total PCBs	<50
	Franks Branch	2-FNK001.12	11/26/2001	Total PCBs	<20
	Horsepen Creek	2-HEP001.27	5/22/2002	Total PCBs	<20

[1] The probable effect concentration for PCB toxicity in sediment is 676 ug/kg (MacDonald *et al.*, 2000), so values above that threshold are shown in red.

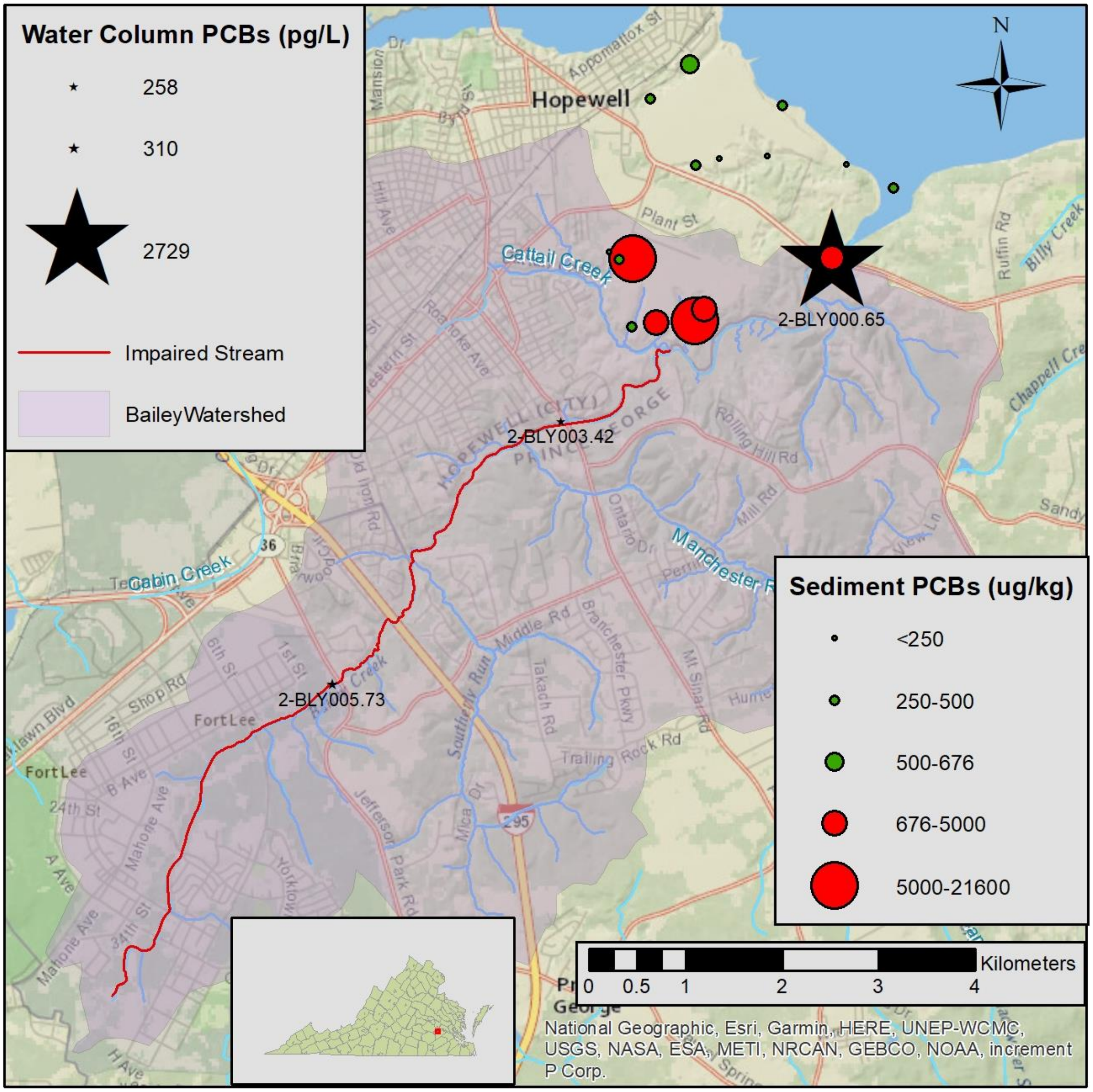

Figure 39. Polychlorinated biphenyl (PCB) concentrations in sediments from Bailey Creek and surrounding area.

2.4.14. Sediment Toxics - Pesticides

Eleven pesticides were analyzed in sediments collected from eight stations within the James River Tributaries Project area. The streams, sample collection dates, and pesticides analyzed are shown in Table 17. The group of pesticides measured represents organochlorine compounds that are persistent in the environment, toxic, and bioaccumulative. These characteristics make them potential candidates for causing toxic stress to the benthic community. In all of the samples collected, all of the measured pesticides were below the detection limit. This means that persistent pesticides are not likely a stressor in these streams. While pesticides were not detected in water and sediments from James River Tributary Project streams, the pesticides aldrin and heptachlor epoxide were measured in fish tissue above DEQ screening levels in Bailey Creek (2-BLY005.72) in 1997. Samples of American eel and torrent sucker both exceeded the aldrin screening level of 6.3 ppb, and American eel exceeded the heptachlor epoxide screening level of 10 ppb. Sources of aldrin and heptachlor epoxide in this watershed have not been identified, but these could be potential stressors in Bailey Creek.

Table 17. Pesticides analyzed in sediments of James River Tributaries Project streams.

Watershed	Stream	Station	Date	Pesticides Analyzed
Bailey Creek	Bailey Creek	2-BLY000.65	11/26/2001	ALDRIN
Oldtown Creek	Oldtown Creek	2-OTC001.54	11/26/2001	DDT, DDD, and DDE
Swift Creek	Swift Creek	2-SFT031.08	4/19/2001	DICOFOL
		2-SFT033.42	6/18/2001	DIELDRIN
		2-SFT034.38	7/10/2001	ENDRIN
	Dry Creek	2-DYC000.19	5/7/2001	HEPTACHLOR
	Franks Branch	2-FNK001.12	11/26/2001	HEPTACHLOR EPOXIDE
	Horsepen Creek	2-HEP001.27	5/22/2002	PENTACHLOROPHENOL
				TOXAPHENE

2.4.15. Sediment Toxics - Metals

A total of 16 metals were measured in the sediments of Nuttree Branch, Oldtown Creek, Rohoic Creek, three tributaries of Swift Creek, and three stations on Swift Creek. Levels of these metals in sediments were compared to threshold effect concentrations (TECs) and probable effect concentrations (PECs) from MacDonald *et al.* (2000). TECs are levels below which toxic effects are unlikely, and PECs are levels above which toxic effects are likely. Selected metals with published effect thresholds are shown in Table 18. All metal concentrations in all streams were below PEC values, however, some metals were above TEC values in some streams. One Swift Creek tributary (Dry Creek) exceeded TECs for copper and lead, and one Swift Creek station (2-SFT033.42) exceeded the TEC for copper. Both of these stations are located in Swift Creek Reservoir, which is a water supply for Chesterfield County. The county occasionally applies copper sulfate as an algaecide to spot treat algal blooms in this reservoir. Chesterfield County Water Quality Reports show that 1200, 3000, and 2800 pounds of copper sulfate were applied in 2015, 2016, and 2017, respectively (Chesterfield County, 2016, 2017, 2018). These and other additions of copper sulfate explain the elevated copper levels at the Dry Creek and Swift Creek stations.

Table 18. Metals concentrations in sediments from James River Tributaries Project streams.

Metal	TEC[1] (mg/kg)	PEC[2] (mg/kg)	Average (Range)[3] in mg/kg				
			Nuttree Branch	Oldtown Creek	Rohoic Creek	Swift Creek Tribs	Swift Creek
Arsenic	9.79	33	0.67	2.5	0.15	2.0 (0.67-2.5)	2.5 (2.5-2.5)
Cadmium	0.99	4.98	0.07	0.5	0.07	0.4 (0.07-0.5)	0.5 (0.5-0.5)
Chromium	43.4	111	6.92	2.5	1.42	11 (2.5-28.6)	17 (5.28-35)
Copper	31.6	149	5.06	2.5	1.2	14 (2.5-**46.7**)	15 (2.5-**34.4**)
Lead	35.8	128	5.42	2.5	3.6	13 (2.5-**40.2**)	19 (6-32.4)
Mercury	0.18	1.06	0.025	0.05	0.004	0.04 (0.025-0.05)	0.05 (0.05-0.05)
Nickel	22.7	48.6	2.86	2.5	1.24	6.29 (2.5-16.9)	8.4 (2.5-19.1)
Zinc	121	459	29.9	11.1	3	33 (2.5-90)	39 (11.7-74.9)

[1] TEC is the consensus-based Threshold Effect Concentration from MacDonald *et al*., 2000.
[2] PEC is the consensus-based Probable Effect Concentration from MacDonald *et al*., 2000.
[3] Only one sediment sample was available for Nuttree Branch, Oldtown Creek, and Rohoic Creek, so no range information is presented for these streams. Bold maximum values indicate that the value is above TECs but below PECs.

2.4.1. Water Quality Regressions

To investigate the potential role of various water quality parameters impacting the benthic macroinvertebrate community, SCI scores at each station were regressed against water quality parameter values at those sites. Table 19 shows the results of these regressions ordered from most significant to least significant. The only parameter that exhibited a statistically significant regression was habitat. This indicates that as habitat scores increased across stations, benthic scores also increased. The second most predictive water quality parameter was dissolved oxygen, although this regression did not quite meet the $p<0.05$ threshold for statistical significance. The r^2 values for all of the regressions, even habitat, were relatively low. This means that benthic health is responding to a variety of factors, and it is not easily explained by a single water quality parameter across stations.

Table 19. Regression relationship between water quality parameters and stream condition index (SCI) scores.

Parameter	Regression Significant (Y/N)	r^2	p-value
Habitat	Y	0.30	0.04
Dissolved Oxygen	N	0.22	0.08
Total Suspended Solids	N	0.19	0.16
Dissolved Sodium	N	0.18	0.30
Dissolved Sulfate	N	0.13	0.38
Conductivity	N	0.10	0.25
Dissolved Chloride	N	0.10	0.45
Total Volatile Solids	N	0.09	0.43
Total Dissolved Solids	N	0.08	0.48
Temperature	N	0.05	0.41
Total Phosphorus	N	0.03	0.61
Dissolved Potassium	N	0.02	0.76
Ammonia	N	0.01	0.77
pH	N	0.01	0.72
Total Nitrogen	N	0.00	0.93

3.0 OTHER STUDIES

3.1. Fort Lee Environmental Impact Statement

An Environmental Impact Statement (EIS) was prepared for the closure of Fort Lee in the Bailey Creek watershed (U.S. Army Corps of Engineers, 2007). This EIS included an environmental assessment of Bailey Creek and found that:

- No threatened or endangered species were observed to be present during the field survey.
- The stream receives significant amounts of storm water and sediment from Fort Lee, which has resulted in decreased substrate and loss of biological habitat.

- The biological community, including macroinvertebrates and fish, was ranked as poor to moderate.
- There was no evidence of significant releases of contaminants from waste units in the Bailey Creek watershed at the time the survey was conducted.

3.2. Chesterfield County Swift Creek Reservoir Water Quality Monitoring Reports

Swift Creek Reservoir is a recreational lake and public drinking water supply for Chesterfield County. To ensure that the reservoir is meeting its recreational and public water supply uses, the county routinely monitors water quality and reports the results each year. Yearly reports summarize data collected on conventional parameters (temperature, pH, conductivity, and dissolved oxygen), nutrients (phosphorus and nitrogen), E. coli, metals (lead and zinc), algae (chlorophyll-a and algae community structure), and clarity (Secchi depth, suspended solids, and turbidity). Significant findings that potentially impact downstream water quality are summarized below for the three most recent years of data, 2017 (Chesterfield County, 2018), 2018 (Chesterfield County, 2019), and 2019 (Chesterfield County, 2020).

- Dissolved oxygen – The reservoir naturally thermally stratifies during the summer months. Stratification develops in April to May and lasts until October to November. During stratification, all stations met the 4.0 mg/L DO minimum standard in the epilimnion. While hypolimnetic DO levels were not reported, dissolved oxygen is typically depleted in the hypolimnion during stratification. Low dissolved oxygen hypolimnetic waters could impact downstream water quality when the lake level is below the spillway and seepage from the dam constitutes the majority of downstream flow.
- Nutrient enrichment – Chlorophyll-a and total phosphorus levels in two of the last three years have exceeded the Virginia water quality standards for this lake (90^{th} percentile chlorophyll-a concentration of 35 ug/L and median total phosphorus concentration of 40 ug/L). The 90^{th} percentile chlorophyll-a levels were 41.9, 49.1, and 29.1 ug/L in 2017, 2018, and 2019, respectively. The median total phosphorus levels were 67, 48, and 30 ug/L in 2017, 2018, and 2019, respectively. Median total phosphorus levels in 2017 and

2018 were the highest levels measured in the lake since monitoring began in 1992, but levels returned to normal in 2019. Nuisance algae continues to be a problem in the lake, with blue-green algae comprising 28-36% of the algal community. Algaecide treatment was conducted in 2017 with the addition of copper sulfate and in 2018 with the addition of sodium carbonate peroxyhydrate. Algaecide treatment was not needed in 2019. In general, the lake shows signs of nutrient enrichment, although the degree of enrichment and the observed effects vary from year to year. High levels of phosphorus and chlorophyll-a in 2018 may have been associated with higher than normal rainfall during the year (62.91 inches compared to the long-term average of 43.45 inches).

- Solids – Median turbidity in the lake was 5.5 NTU in 2017, 6.2 NTU in 2018, and 5.4 NTU in 2019. Median total suspended solids was 4.4 mg/L in 2017, 5.2 mg/L in 2018, and 4.6 mg/L in 2019. Secchi depths ranged from 1.5 to 3.4 feet. These parameters indicate moderate clarity in the lake.

3.3. Citizen Monitoring Data

Various citizen and non-agency monitoring groups have collected data on James River Tributaries Project streams since 2000. These data are sent to VDEQ and may or may not be included in water quality assessments based on the level of quality assurance and approval by VDEQ. All citizen and non-Agency data submitted to VDEQ between 2000 and 2020 was reviewed and summarized. This included over 2000 data points from 21 stations in Nuttree Branch, Oldtown Creek, Proctors Creek, and Swift Creek. Relevant parameters from these stations included temperature, pH, dissolved oxygen, and conductivity.

Table 20 summarizes temperature data from citizen monitoring locations. Like VDEQ data, temperatures varied throughout the year, but averaged 13.7 to 16.5 °C. Average temperatures were highest in Swift Creek, where the reservoirs and impoundments increase surface area and solar heating. No results from any of the monitored stations exceeded the Virginia water quality standard of 32°C. This is consistent with VDEQ data, where all non-tidal stations met water quality standards for temperature.

Table 21 summarizes pH data from citizen monitoring locations. Average pH values ranged from 5.83 in Proctors Creek to 6.54 in Swift Creek. These values are consistently lower than average pH values measured by VDEQ, which ranged from 6.38 to 6.79 for these streams. pH results from citizen monitoring were below the Virginia water quality standard of 6.0 in 16% of samples from Nuttree Branch, 5% from Oldtown Creek, 64% from Proctors Creek, and 2% from Swift Creek. This varies moderately from VDEQ results, where 3.8% of samples from Nuttree Branch, 10.3% from Oldtown Creek, 7.0% from Proctors Creek, and 0.3% from Swift Creek were below 6.0. This discrepancy is likely due to the fact that in much of the citizen monitoring data, pH values were only measured to the nearest 0.5 pH unit. This means that the resolution of values near the cutoff of 6.0 is very low. Differences can also be attributed to different sampling locations on these streams. Despite these discrepancies, the overall picture of pH in these streams remains the same. All are on the acidic side of neutral, and some (particularly Proctors Creek and Oldtown Creek) routinely fall below water quality standards for pH.

Table 22 summarizes the dissolved oxygen data from citizen monitoring. Average DO values ranged from 7.74 in Swift Creek to 8.61 in Oldtown Creek. This is consistent with VDEQ data, where DO averaged 7.75 and 8.90 in these two streams, respectively. Citizen monitoring data was below the minimum DO standard of 5.0 mg/L in 15% of samples from Nuttree Branch, 6% from Oldtown Creek, 16% from Proctors Creek, and 17% from Swift Creek. Compared to VDEQ data, these values were relatively consistent for Nuttree Branch and Swift Creek, where DO fell below 5.0 mg/L 20% of the time (at 2-NUT002.22) and 25% of the time, respectively. Citizen monitoring results were less consistent with VDEQ results in Oldtown Creek and Proctors Creek, where VDEQ recorded 16% and 2.8% of samples below 5.0 mg/L, respectively. These differences are likely due to the differences in sampling location. Even among VDEQ stations on the same stream, DO values can vary considerably based on local conditions of depth and velocity. Overall, citizen monitoring data corroborated VDEQ findings that DO is certainly a stressor in Swift Creek, likely a stressor in Oldtown Creek and Proctors Creek, and may be a stressor in Nuttree Branch.

Table 23 summarizes the conductivity data from citizen monitoring. Average conductivity values averaged 118 uS/cm in Nuttree Branch, 57 uS/cm in Oldtown Creek, and 89 uS/cm in Proctors Creek. These averages are consistent with VDEQ averages for Oldtown Creek (67 uS/cm at 2-OTC005.38) and Proctors Creek (84 uS/cm), but are lower than VDEQ data in Nuttree Branch (256 uS/cm). No conductivity values in citizen monitoring data exceeded 500 uS/cm. This is also consistent with VDEQ data, where only occasional samples exceeded this value.

Table 20. Summary of temperature data collected through citizen monitoring program.

Stream	Sites	Samples	Min (ºC)	Max (ºC)	Average (ºC)	Results >32	%Results >32
Nuttree Branch	4	83	3.0	29.0	15.6	0	0
Oldtown Creek	2	53	1.0	26.0	13.7	0	0
Proctors Creek	2	55	2.6	28.0	15.1	0	0
Swift Creek	4	153	3.0	32.0	16.5	0	0

Table 21. Summary of pH data collected through citizen monitoring program.

Stream	Sites	Samples	Min	Max	Average	Results <6.0	%Results <6.0
Nuttree Branch	4	104	5.50	7.50	6.36	17	16%
Oldtown Creek	3	63	5.64	6.53	6.16	3	5%
Proctors Creek	2	55	4.97	7.49	5.83	35	64%
Swift Creek	13	682	5.00	8.00	6.54	11	2%

Table 22. Summary of dissolved oxygen data collected through citizen monitoring program.

Stream	Sites	Samples	Min (mg/L)	Max (mg/L)	Average (mg/L)	Results <5.0	%Results <5.0
Nuttree Branch	3	80	1.80	14.34	7.78	12	15%
Oldtown Creek	3	31	3.40	12.78	8.61	2	6%
Proctors Creek	2	55	1.62	13.54	8.47	9	16%
Swift Creek	12	576	1.00	15.30	7.74	98	17%

Table 23. Summary of conductivity data collected through citizen monitoring program.

Stream	Sites	Samples	Min (uS/cm)	Max (uS/cm)	Average (uS/cm)	Results >500	%Results >500
Nuttree Branch	1	21	60	233	118	0	0%
Oldtown Creek	1	11	47	67	57	0	0%
Proctors Creek	2	55	44	259	89	0	0%

4.0 CAUSAL ANALYSIS

JMU conducted this stressor identification analysis according to EPA's Stressor Identification Guidance Document (USEPA, 2000b) using the Causal Analysis/Diagnosis Decision Information System (CADDIS) (USEPA, 2018a). The CADDIS approach provides guidance on evaluating various lines of evidence to determine the cause of biological impairments. In the case of the James

River Tributaries Project, JMU used the available data collected from the site, published water quality standards and threshold values, and available literature from other cases to investigate the potential causes of impairment in each of the impaired streams. Table 24 shows the lines of evidence suggested by the CADDIS approach, an explanation of the concept, and examples of how these lines of evidence were analyzed in this project. Some lines of evidence were not applicable, such as the analysis of biomarkers, field manipulations, or laboratory experiments. The majority of the lines of evidence, however, were investigated for this project.

Table 24. Lines of evidence used in the causal analysis approach.

Evidence	The Concept	Examples from this Project
	Data from the Case	
Spatial Co-occurrence	The biological effect must be observed where the cause is observed, and must not be observed where the cause is absent.	Analysis of water quality and habitat data across stations
Temporal Co-occurrence	The biological effect must be observed when the cause is observed, and must not be observed when the cause is absent.	Analysis of temporal trends in benthic data
Evidence of Exposure or Biological Mechanism	Measurements of the biota show that relevant exposure to the cause has occurred, or that other biological mechanisms linking the cause to the effect have occurred.	NA
Causal Pathway	Steps in the pathways linking sources to the cause can serve as supplementary or surrogate indicators that the cause and the biological effect are likely to have co-occurred.	Development and analysis of causal pathways for stressors
Stressor-Response Relationships from the Field	As exposure to the cause increases, intensity or frequency of the biological effect increases; as exposure to the cause decreases, intensity or frequency of the biological effect decreases.	Correlation of water quality data with benthic score
Manipulation of Exposure	Field experiments or management actions that increase or decrease exposure to a cause must increase or decrease the biological effect.	NA
Laboratory Tests of Site Media	Controlled exposure in laboratory tests to causes (usually toxic substances) present in site media should induce biological effects consistent with the effects observed in the field.	NA
Temporal Sequence	The cause must precede the biological effect.	Analysis of temporal trends in benthic data
Verified Predictions	Knowledge of a cause's mode of action permits prediction and subsequent confirmation of previously unobserved effects.	NA
Symptoms	Biological measurements (often at lower levels of biological organization than the effect) can be characteristic of one or a few specific causes.	Analysis of benthic metrics, community composition, and functional feeding groups
Data from Elsewhere		
Stressor-Response Relationships from Other Field Studies	At the impaired sites, the cause must be at levels sufficient to cause similar biological effects in other field studies.	Water quality comparison with reference stations and stressor probability thresholds

Stressor-Response Relationships from Laboratory Studies	At the impaired sites, the cause must be at levels associated with related biological effects in laboratory studies.	Water quality comparison with VA water quality standards and literature threshold values
Stressor-Response Relationships from Simulation Models	At the impaired sites, the cause must be at levels associated with effects in mathematical models simulating ecological processes.	Confirmation through use of TMDL model
Mechanistically Plausible Cause	The relationship between the cause and biological effect must be consistent with known principles of biology, chemistry and physics.	Development and analysis of causal pathways for stressors
Manipulation of Exposure at Other Sites	Field experiments or management actions at other sites that increase or decrease exposure to a cause must increase or decrease the biological effect.	Confirmation through literature
Analogous Stressors	Agents similar to the causal agent at the impaired site should lead to similar effects at other sites.	Confirmation through literature
Multiple Types of Evidence		
Consistency of Evidence	Confidence in the argument for or against a cause is increased when many types of evidence consistently support or weaken it.	Weight of evidence approach
Explanation of the Evidence	Confidence in the argument for a candidate cause is increased when a post hoc mechanistic, conceptual, or mathematical model reasonably explains any inconsistent evidence.	Confirmation through use of TMDL model

For each impairment and for each potential candidate cause, the applicable lines of evidence were evaluated. For each line of evidence, the candidate cause was scored on a 3-point positive and negative scale (Table 25). This scale represents the strength of the evidence for or against each candidate cause. A weight of evidence approach was then used to sum the respective scores and classify candidate causes as either non-stressors, possible stressors, or probable stressors. If the summed scores for candidate causes were ≤0, the cause was classified as a non-stressor. If scores were 1-3, the cause was classified as a possible stressor. If scores were >3, the cause was classified as a probable stressor (Table 26).

Table 25. Scoring criteria used to evaluate candidate stressors.

Score	Explanation
+3	The line of evidence **strongly supports** the candidate stressor as the cause of the impairment
+2	The line of evidence **moderately supports** the candidate stressor as the cause of the impairment
+1	The line of evidence **weakly supports** the candidate stressor as the cause of the impairment
0	The line of evidence **does not support or refute** the candidate stressor as the cause of the impairment
-1	The line of evidence **weakly refutes** the candidate stressor as the cause of the impairment
-2	The line of evidence **moderately refutes** the candidate stressor as the cause of the impairment
-3	The line of evidence **strongly refutes** the candidate stressor as the cause of the impairment

Table 26. Scheme for classifying candidate causes based on causal analysis.

Total Score	Classification
<-2	Non-Stressor
-1	
0	
+1	Possible Stressor
+2	
+3	
+4	Probable Stressor
+5	
>+6	

4.1. Temperature

Table 27 shows the causal analysis results for temperature across James River Tributaries Project streams. Total causal analysis scores ranged from -20 to -16, indicating that there is strong evidence that temperature is a non-stressor in these streams. No violations of the temperature standard were observed at any of the benthic monitoring stations even during summertime diurnal monitoring, when critical conditions should be observed. All streams except for Swift Creek were similar in temperature to the unimpaired reference. For these reasons and others explained in Table 27, temperature was categorized as a non-stressor.

Table 27. Causal analysis results for temperature as a stressor.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	-3	-3	-3	-3	-3	-2	Temperature levels at all benthic stations were below the maximum WQS. Temperature in Swift Creek was significantly higher than in the reference, but below the WQS.
Temporal Co-occurrence	-3	-3	-3	-3	-3	-3	At the time of benthic sample collection, temperatures at all sites met water quality standards.
Causal Pathway	-1	1	1	1	2	-1	Riparian vegetation was significantly lower in Nuttree Branch, Oldtown Creek, Proctors Creek, and Rohoic Creek than in the reference. This can provide a causal pathway for solar heating to increase water temperatures. Riparian vegetation was the lowest in Rohoic Creek, where trees are eliminated due to a high voltage power line. Riparian vegetation in Bailey Creek and Swift Creek was not significantly different from the reference.
Stressor-Response Relationships from the Field	-3	-3	-3	-3	-3	-3	Temperature was not significantly correlated with benthic health across sites.
Temporal Sequence	-3	-2	-2	-3	-3	-3	If high temperature were the primary stressor, benthic scores would be expected to be lower in the fall following high summer temperatures. In contrast, benthic scores in Bailey Creek, Proctors Creek, Rohoic Creek, and Swift Creek were higher in the fall than in the spring. The remaining streams saw no seasonal pattern.
Symptoms	0	0	0	0	0	0	None of the streams exhibited symptoms that would specifically indicate temperature as a primary stressor. All streams exhibited a lack of richness of sensitive species (EPT taxa), but this could indicate almost any physical or chemical stressor.
Stressor-Response Relationships from Other Field Studies	-2	-2	-2	-2	-2	1	Temperature in Swift Creek was significantly higher than in the reference, but below the WQS. Temperature in all other streams was consistent with the reference.
Stressor-Response Relationships from Laboratory Studies	-3	-3	-3	-3	-3	-3	Temperature levels at all benthic stations were below the maximum WQS.
Consistency of Evidence	-2	-2	-2	-2	-2	-2	Weight of evidence consistently refuted temperature as a primary stressor.
Sum	**-20**	**-17**	**-17**	**-18**	**-17**	**-16**	

4.2. pH

Table 28 shows the causal analysis results for pH across James River Tributaries Project streams. Total causal analysis scores ranged from -31 to -22 in Bailey Creek, Nuttree Branch, Rohoic Creek, and Swift Creek, indicating that there is strong evidence that pH is a non-stressor in these streams. However, scores in Oldtown Creek and Proctors Creek were +11 and +12, respectively, indicating that pH is a probable in these streams. pH values were below the water quality standard 10.3% of the time in Oldtown Creek and 7.0% of the time in Proctors Creek. Minimum recorded pH values were 5.3 and 5.4 in these streams, respectively. In addition, diurnal sampling in Proctors Creek revealed that pH remained below 6 for 5 days. The remaining streams did not exhibit violations of the pH standard at benthic monitoring stations (with the exception of 1 sample in Bailey Creek). For these reasons and others explained in Table 28, pH was categorized as a non-stressor in Bailey Creek, Nuttree Branch, Rohoic Creek, and Swift Creek, but was categorized as a probable stressor in Oldtown Creek and Proctors Creek.

Table 28. Causal analysis results for pH as a stressor.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	-1	-3	2	2	-3	-3	In Nuttree Branch, Rohoic Creek, and Swift Creek, all benthic station pH values were within the low probability range for stressor effects. In Bailey Creek, 2.5% of samples had pH below 6 and were in the medium probability range for stressor effects. In Oldtown Creek and Proctors Creek, 10.3% and 7.0% of samples had pH below 6. During diurnal sampling, pH in Proctors Creek remained below 6 for 5 days.
Temporal Co-occurrence	-3	-3	1	2	-3	-3	At the time of benthic sample collection, pH at all sites (except for Oldtown Creek and Proctors Creek) was in the low probability range for stressor effects. In Oldtown Creek, one pH recording below the WQS was observed on the day of an impaired benthic sampling. In Proctors Creek, pH was below the water quality standard on 2 of the 5 impaired benthic sampling days.
Causal Pathway	-3	-3	2	3	-3	-3	The causal pathway from wetland decomposition to low pH from organic acid formation is intact for Oldtown Creek and Proctors Creek. This pathway includes ample wetlands within

							the watersheds, high dissolved organic matter, redwater or blackwater conditions, and low pH. No other streams exhibited evidence of this pathway.
Stressor-Response Relationships from the Field	-3	-3	-3	-3	-3	-3	pH was not significantly correlated with benthic health across sites.
Temporal Sequence	-3	-3	-2	-2	-3	-3	pH levels were consistently in an acceptable range in Bailey Creek, Nuttree Branch, Rohoic Creek, and Swift Creek. In Oldtown Creek and Proctors Creek, low pH did not consistently precede benthic impairments.
Symptoms	1	-2	2	2	-2	-2	% Ephemeroptera were significantly lower in Bailey Creek, Oldtown Creek, and Proctors Creek than in the reference. Courtney and Clements (1998) reported that Ephemeroptera were the most sensitive order to low pH conditions.
Stressor-Response Relationships from Other Field Studies	-1	-3	2	1	-3	-3	Oldtown Creek had significantly lower pH than the reference site. The average pH at all sites was within the low probability range for stressor effects, but 2.5% of samples in Bailey Creek, 10.3% in Oldtown Creek, and 7.0% in Proctors Creek were in the medium probability range for stressor effects.
Stressor-Response Relationships from Laboratory Studies	-1	-3	2	3	-3	-3	In Nuttree Branch, Rohoic Creek, and Swift Creek, all benthic station pH values were within WQSs. In Bailey Creek, Oldtown Creek, and Proctors Creek, pH values were below the WQS in 2.5%, 10.3%, and 7.0% of samples, respectively. During diurnal sampling, pH in Proctors Creek remained below 6 for 5 days.
Mechanistically Plausible Cause	-3	-3	2	3	-3	-3	The causal pathway from wetland decomposition to low pH from organic acid formation is intact for Oldtown Creek and Proctors Creek. This pathway includes ample wetlands within the watersheds, high dissolved organic matter, redwater or blackwater conditions, and low pH. No other streams exhibited evidence of this pathway.
Analogous Stressors	-3	-2	2	0	-2	-2	An analogous parameter to pH was alkalinity. Alkalinity was very low in Oldtown Creek, consistent with low pH.
Consistency of Evidence	-2	-3	1	1	-3	-3	Weight of evidence consistently refuted pH as a primary stressor in Bailey Creek, Nuttree Branch, Rohoic Creek, and Swift Creek, but the weight of evidence marginally supported pH as a stressor in Oldtown Creek and Proctors Creek.
Sum	**-22**	**-31**	**11**	**12**	**-31**	**-31**	

4.3. Dissolved Oxygen

Table 29 shows the causal analysis results for dissolved oxygen across James River Tributaries Project streams. Total causal analysis scores ranged from -1 to +11. Dissolved oxygen was categorized as a non-stressor in Bailey Creek, where the total causal analysis scores was -1.

Dissolved oxygen was not observed below 5.0 mg/L during periodic measurements in Bailey Creek. Dissolved oxygen was categorized as a possible stressor in Nuttree Branch, Proctors Creek, and Rohoic Creek where total causal analysis scores were 1-3. In Proctors Creek, 3% of periodic DO measurements were below 5.0 mg/L. In Nuttree Branch, no DO measurements at the benthic station were below 5.0 mg/L, but 20% of measurements were below 5.0 mg/L at an upstream monitoring station. In Rohoic Creek 10% of measurements were below 5.0 mg/L at an upstream station, and diurnal DO dropped below 5. 0 mg/L. In Oldtown Creek and Swift Creek, dissolved oxygen was categorized as a probable stressor with causal analysis scores of 7 and 11, respectively. In Oldtown Creek, 15% of periodic DO measurements were below 5.0 mg/L. In Swift Creek, 25% of periodic DO measurements were below 5.0 mg/L, and diurnal DO measurements violated daily average and daily minimum water quality standards. Additional rationale for stressor categorizations is explained in Table 29.

Table 29. Causal analysis results for dissolved oxygen as a stressor.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	1	1	2	2	1	3	In Swift Creek, 25% of periodic measurements were below 5.0 mg/L, and diurnal DO measurements violated daily average and daily minimum WQSs. In Oldtown Creek, 15% of periodic measurements were below 5.0 mg/L. In Proctors Creek, 3% of periodic measurements were below 5.0 mg/L. No periodic measurements in Bailey Creek, Nuttree Branch, and Rohoic Creek were below 5.0 mg/L, but periodic and diurnal measurements were in the high probability range for stressor effects in these streams.
Temporal Co-occurrence	-2	-2	-2	-2	-2	1	At the time of benthic sample collection, DO at all sites (except for Swift Creek) was in the low to medium probability range for stressor effects. In Swift Creek, one DO measurement in the high probability range for stressor effects was observed on the day of an impaired benthic sampling.
Causal Pathway	1	1	2	2	1	2	Swift Creek, Oldtown Creek, and Proctors Creek have moderate evidence supporting a possible causal pathway, and the remaining streams have weak evidence. In Swift Creek, the pathway includes low slope, upstream impoundments, decomposition of deposited organic material and possibly nutrient enrichment. In Bailey Creek, Oldtown Creek and Proctors Creek, the pathway includes decomposition of

							dissolved or deposited organic matter. In Nuttree Branch and Rohoic Creek, the pathway may include nutrient enrichment.
Stressor-Response Relationships from the Field	1	1	1	1	1	1	DO was not significantly correlated with benthic health at the alpha = 0.05 level, but it was significant at the alpha = 0.1 level (p=0.08).
Temporal Sequence	-2	-1	-1	-2	-2	-2	DO levels were lowest in the late summer and fall, yet Bailey Creek, Proctors Creek, Rohoic Creek, and Swift Creek exhibited higher fall benthic scores than spring scores. Benthic scores were consistent between fall and spring in Nuttree Branch and Oldtown Creek.
Symptoms	-1	-1	-1	-1	-1	-1	Biological condition gradient analysis did not identify predominant taxa in any streams that exclusively implicated DO as a stressor. Biological condition gradient analysis ranked DO 5-7 out of the 10 stressors evaluated, indicating that organism tolerance patterns implicated other stressors before DO.
Stressor-Response Relationships from Other Field Studies	2	1	3	2	2	3	Bailey Creek, Oldtown Creek, Proctors Creek, and Swift Creek had statistically lower DO than the reference. DO in Oldtown Creek and Swift Creek averaged in the medium probability range for stressor effects, while the remaining streams averaged in the no to low probability range. During diurnal monitoring, all streams exhibited nighttime DOs in the high probability range for stressor effects.
Stressor-Response Relationships from Laboratory Studies	-1	2	2	1	1	3	In Swift Creek, 25% of periodic measurements were below 5.0 mg/L, and diurnal measurements violated daily average and daily minimum WQSs. At an upstream Nuttree Branch station, 20% of periodic measurements were below 5.0 mg/L, but no measurements at the benthic station were below this value. In Oldtown Creek, 15% of periodic measurements were below 5.0 mg/L, but diurnal measurements only briefly dropped below this value. In Proctors Creek, 3% of periodic measurements were below 5.0 mg/L, but no diurnal measurements were below this value. No periodic measurements in Bailey Creek or Rohoic Creek were below the WQS, but diurnal measurements in Rohoic Creek were briefly below 5.0 mg/L.
Consistency of Evidence	0	0	1	0	0	1	Weight of evidence weakly supported DO as a stressor in Swift Creek and Oldtown Creek, but evidence was ambiguous for the other streams.
Sum	**-1**	**2**	**7**	**3**	**1**	**11**	

4.4. Conductivity and Total Dissolved Solids

Table 30 shows the causal analysis results for conductivity and total dissolved solids across James River Tributaries Project streams. Total causal analysis scores ranged from -24 to -13, indicating that there is strong evidence that conductivity and total dissolved solids are non-stressors in these streams. Average conductivity and total dissolved solids measurements in all streams were in the no to low probability range for stressor effects. Only a single excursion into the high probability range was observed in Nuttree Branch and Rohoic Creek. These incidents appeared to be associated with road salt application and stormwater runoff. Typical conductivity levels in each of the streams were relatively low. For these reasons and others explained in Table 30, conductivity and total dissolved solids were categorized as non-stressors.

Table 30. Causal analysis results for conductivity and dissolved solids.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	-3	-2	-3	-3	-2	-3	Average conductivity and total dissolved solids measurements were in the no to low probability range for stressor effects. Several individual excursions into the medium to high range occurred in Nuttree Branch and Rohoic Creek.
Temporal Co-occurrence	-3	-3	-3	-3	1	-3	At the time of benthic sample collection, conductivity at all sites (except for Rohoic Creek) was in the no to low probability range for stressor effects. In Rohoic Creek, one conductivity recording in the high probability range for stressor effects was observed on the day of an impaired benthic sampling.
Causal Pathway	1	2	0	1	2	0	Bailey Creek, Nuttree Branch, Proctors Creek, and Rohoic Creek all exceeded 15% imperviousness, which means that solids and salts on surfaces can easily runoff increasing conductivity and dissolved solids. This was intermittently observed in Nuttree Branch and Rohoic Creek through occasionally high conductivity readings after storm events. Imperviousness in Oldtown Creek and Swift Creek watersheds was in the 8-13% range.
Stressor-Response Relationships from the Field	-3	-3	-3	-3	-3	-3	Conductivity and total dissolved solids were not significantly correlated with benthic health across sites.
Temporal Sequence	-3	-2	-3	-3	-2	-3	Conductivity levels were consistently low in Bailey Creek, Oldtown Creek, Proctors Creek, and Swift Creek. In Nuttree Branch and Rohoic Creek, high levels did not consistently precede benthic impairments.
Symptoms	-1	-1	-1	-1	-1	-1	None of the streams exhibited symptoms that would specifically indicate conductivity as a primary stressor. All streams exhibited a lack of richness of sensitive species (EPT taxa), but this could indicate almost any physical or chemical stressor. Conductivity ranked 4th, 5th, or 6th among stressors in the biological condition gradient analysis.

Stressor-Response Relationships from Other Field Studies	-3	-2	-3	-3	-2	-3	Average conductivity and total dissolved solids measurements were in the no to low probability range for stressor effects. Several individual excursions into the medium to high range occurred in Nuttree Branch and Rohoic Creek.
Stressor-Response Relationships from Laboratory Studies	-3	-2	-3	-3	-2	-3	Only a single measured value at Nuttree Branch and a single measured value at Rohoic Creek exceeded the conductivity threshold of 500 uS/cm reported by Pond (2004).
Analogous Stressors	-3	-2	-3	-3	-3	-3	Similar to conductivity, total dissolved solids were in the no to low probability range for stressor effects, with the exception of one value in the medium range in Nuttree Branch.
Multiple Types of Evidence							
Consistency of Evidence	-2	-1	-2	-2	-1	-2	Weight of evidence consistently refuted conductivity as a primary stressor.
Sum	**-23**	**-16**	**-24**	**-23**	**-13**	**-24**	

4.5. Dissolved Ions

4.5.1. Sodium

Table 31 shows the causal analysis results for dissolved sodium across James River Tributaries Project streams. In all of the streams except Nuttree Branch, total causal analysis scores ranged from -16 to -3, indicating that there is moderate to strong evidence that dissolved sodium is a non-stressor in these streams. In Nuttree Branch, the total causal analysis score was +1, indicating that dissolved sodium is a possible stressor. Average sodium levels were in the high probability range for stressor effects in Nuttree Branch, but were in the low to medium probability range for all other streams. While sodium levels were elevated in Nuttree Branch, the levels were still well below toxic thresholds reported by Mount *et al.* (2016). For this reason and others explained in Table 31, dissolved sodium was categorized as a possible stressor in Nuttree Branch. Dissolved sodium was categorized as a non-stressor in all other streams.

Table 31. Causal analysis results for dissolved sodium.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation

Spatial Co-occurrence	1	3	1	1	2	-2	Average sodium levels were in the high probability range for stressor effects in Nuttree Branch, low probability range in Swift Creek, and medium probability range for all other streams. However, even the highest levels in Nuttree Branch were well below toxic thresholds from the literature.
Temporal Co-occurrence	-1	-1	-1	-1	-1	-1	At the time of impaired benthic sampling, sodium levels were not observed in the high probability range for stressor effects.
Causal Pathway	1	2	0	1	2	0	Bailey Creek, Nuttree Branch, Proctors Creek, and Rohoic Creek all exceeded 15% imperviousness, which means that solids and salts on surfaces can easily runoff increasing dissolved solids. Nuttree Branch and Rohoic Creek exhibited higher sodium levels, averaging in the high probability range for stressor effects in Nuttree Branch and at the upper end of the medium probability range in Rohoic Creek. Imperviousness in Oldtown Creek and Swift Creek watersheds was in the 8-13% range.
Stressor-Response Relationships from the Field	-2	-2	-2	-2	-2	-2	Dissolved sodium was not significantly correlated with benthic health across sites.
Temporal Sequence	-2	-1	-1	-2	-2	-2	Sodium levels were generally highest in the fall, yet Bailey Creek, Proctors Creek, Rohoic Creek, and Swift Creek exhibited higher fall benthic scores than spring scores. Benthic scores were consistent between fall and spring in Nuttree Branch and Oldtown Creek.
Symptoms	0	0	0	0	0	0	None of the streams exhibited symptoms that would specifically indicate sodium as a primary stressor. All streams exhibited a lack of richness of sensitive species (EPT taxa), but this could indicate almost any physical or chemical stressor. Biological condition gradient analysis indicated a combination of sediment and nutrient enrichment as the highest ranked stressors.
Stressor-Response Relationships from Other Field Studies	1	3	1	1	2	-2	Sodium levels in all streams were statistically higher than in the reference. Average sodium levels were in the high probability range for stressor effects in Nuttree Branch, low probability range in Swift Creek, and medium probability range for all other streams.
Stressor-Response Relationships from Laboratory Studies	-3	-2	-3	-3	-2	-3	Literature thresholds for sodium toxicity (Mount et al., 2016) were orders of magnitude higher than dissolved sodium levels observed in any of the streams.
Analogous Stressors	-2	-1	-2	-2	-1	-2	Conductivity, which would increase with increasing ions, did not appear to be a primary stressor in these streams.
Multiple Types of Evidence							
Consistency of Evidence	-1	0	-1	-1	-1	-2	Weight of evidence was ambiguous for Nuttree Branch, but weakly refuted sodium as a primary stressor in the other streams.
Sum	**-8**	**1**	**-8**	**-8**	**-3**	**-16**	

4.5.2. Potassium

Table 32 shows the causal analysis results for dissolved potassium across James River Tributaries Project streams. Total causal analysis scores ranged from -11 to -8, indicating that there is moderate to strong evidence that dissolved potassium is a non-stressor in these streams. In each stream, average dissolved potassium values were in the medium probability range for stressor effects, and no values were in the high probability range. Values were also well below toxic thresholds reported by Mount *et al.* (2016). For these reasons and others explained in Table 32, dissolved potassium was categorized as a non-stressor.

Table 32. Causal analysis results for dissolved potassium.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	1	1	1	1	1	1	Average dissolved potassium levels in all of the streams were in the medium probability range for stressor effects. No values were in the high probability range.
Temporal Co-occurrence	-1	-1	-1	-1	-1	-1	At the time of impaired benthic sampling, potassium levels were not observed in the high probability range for stressor effects.
Causal Pathway	1	1	0	1	1	0	Bailey Creek, Nuttree Branch, Proctors Creek, and Rohoic Creek all exceeded 15% imperviousness, which means that solids and salts on surfaces can easily runoff increasing dissolved solids. Imperviousness in Oldtown Creek and Swift Creek watersheds was lower, in the 8-13% range.
Stressor-Response Relationships from the Field	-3	-3	-3	-3	-3	-3	Dissolved potassium was not significantly correlated with benthic health across sites.
Temporal Sequence	-2	-1	-1	-2	-2	-2	Potassium levels were generally highest in the fall, yet Bailey Creek, Proctors Creek, Rohoic Creek, and Swift Creek exhibited higher fall benthic scores than spring scores. Benthic scores were consistent between fall and spring in Nuttree Branch and Oldtown Creek.
Symptoms	0	0	0	0	0	0	None of the streams exhibited symptoms that would specifically indicate potassium as a primary stressor. All streams exhibited a lack of richness of sensitive species (EPT taxa), but this could indicate almost any physical or chemical stressor. Biological condition gradient analysis indicated a combination of sediment and nutrient enrichment as the highest ranked stressors.

Stressor-Response Relationships from Other Field Studies	1	1	1	-1	1	1	Potassium levels in all streams except for Proctors Creek were statistically higher than in the reference. Average potassium levels were in the medium probability range for stressor effects in all streams.
Stressor-Response Relationships from Laboratory Studies	-3	-3	-3	-3	-2	-3	Literature thresholds for potassium toxicity (Mount et al., 2016) were approximately 10 times higher than dissolved potassium levels observed in any of the streams.
Analogous Stressors	-2	-2	-2	-2	-2	-2	Conductivity, which would increase with increasing ions, did not appear to be a primary stressor in these streams.
Consistency of Evidence	-1	-1	-1	-1	-1	-1	Weight of evidence weakly refuted potassium as a primary stressor in these streams.
Sum	**-9**	**-8**	**-9**	**-11**	**-8**	**-10**	

4.5.3. Chloride

Table 33 shows the causal analysis results for dissolved chloride across James River Tributaries Project streams. In all of the streams except Rohoic Creek, total causal analysis scores ranged from -17 to -7, indicating that there is moderate to strong evidence that dissolved sodium is a non-stressor in these streams. In Rohoic Creek, the total causal analysis score was +1, indicating that dissolved chloride is a possible stressor. Average chloride levels were in the high probability range for stressor effects in Rohoic Creek, but were in the low to medium probability range for all other streams. While chloride levels were elevated in Rohoic Creek, the levels were still well below the water quality standard of 230 mg/L. For this reason and others explained in Table 33, dissolved chloride was categorized as a possible stressor in Rohoic Creek. Dissolved chloride was categorized as a non-stressor in all other streams.

Table 33. Causal analysis results for dissolved chloride.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	-2	1	-2	-2	3	-2	Average dissolved chloride levels in Bailey Creek, Oldtown Creek, Proctors Creek, and Swift Creek were in the low probability range for stressor effects. Chloride levels in Nuttree Branch averaged in the medium probability range for stressor effects, and chloride levels in Rohoic Creek averaged in the high probability range for stressor effects.

Temporal Co-occurrence	-1	-1	-1	-1	1	-1	At the time of benthic sample collection, chloride in one Rohoic Creek sample was in the high probability range for stressor effects. No other stream exhibited high chloride levels on the day of an impaired benthic sampling.
Causal Pathway	1	1	0	1	1	0	Bailey Creek, Nuttree Branch, Proctors Creek, and Rohoic Creek all exceeded 15% imperviousness, which means that solids and salts on surfaces can easily runoff increasing dissolved solids. Imperviousness in Oldtown Creek and Swift Creek watersheds was lower, in the 8-13% range.
Stressor-Response Relationships from the Field	-2	-2	-2	-2	-2	-2	Dissolved chloride was not significantly correlated with benthic health across sites.
Temporal Sequence	-2	-1	-1	-2	-2	-2	Chloride levels were generally highest in the fall, yet Bailey Creek, Proctors Creek, Rohoic Creek, and Swift Creek exhibited higher fall benthic scores than spring scores. Benthic scores were consistent between fall and spring in Nuttree Branch and Oldtown Creek.
Symptoms	-2	-2	-2	-2	-1	-2	None of the streams exhibited symptoms that would specifically indicate chloride as a primary stressor. Biological condition gradient analysis ranked chloride 7-10 out of the 10 stressors evaluated, indicating that organism tolerance patterns implicated other stressors before chloride.
Stressor-Response Relationships from Other Field Studies	-2	1	-2	-2	3	-2	Dissolved chloride levels in all streams were statistically higher than in the reference. Average dissolved chloride levels in Bailey Creek, Oldtown Creek, Proctors Creek, and Swift Creek were in the low probability range for stressor effects. Chloride levels in Nuttree Branch averaged in the medium probability range for stressor effects, and chloride levels in Rohoic Creek averaged in the high probability range for stressor effects.
Stressor-Response Relationships from Laboratory Studies	-2	-2	-2	-2	-1	-2	Dissolved chloride levels in all streams were well below the water quality standard of 230 mg/L.
Analogous Stressors	-2	-1	-2	-2	-1	-2	Conductivity, which would increase with increasing ions, did not appear to be a primary stressor in these streams.
Multiple Types of Evidence							
Consistency of Evidence	-2	-1	-2	-2	0	-2	Weight of evidence was ambiguous for Rohoic Creek, but moderately refuted chloride as a primary stressor in the other streams.
Sum	**-16**	**-7**	**-16**	**-16**	**1**	**-17**	

4.5.4. Sulfate

Table 34 shows the causal analysis results for dissolved sulfate across James River Tributaries Project streams. Total causal analysis scores ranged from -17 to -9, indicating that there is moderate to strong evidence that dissolved sulfate is a non-stressor in these streams. In each stream, average dissolved sulfate values were in the no to low probability range for stressor effects, and only one value (in Bailey Creek) was in the high probability range. Values were also below toxic thresholds reported by Mount *et al.* (2016). For these reasons and others explained in Table 34, dissolved sulfate was categorized as a non-stressor.

Table 34. Causal analysis results for dissolved sulfate.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	-1	-2	-3	-3	-2	-3	Average dissolved sulfate levels in all of the streams were in the no to low probability range for stressor effects. Only one anomalous value from Bailey Creek was in the high probability range.
Temporal Co-occurrence	-1	-1	-1	-1	-1	-1	At the time of impaired benthic sampling, sulfate levels were not observed in the high probability range for stressor effects.
Causal Pathway	1	1	0	1	1	0	Bailey Creek, Nuttree Branch, Proctors Creek, and Rohoic Creek all exceeded 15% imperviousness, which means that solids and salts on surfaces can easily runoff increasing dissolved solids. Imperviousness in Oldtown Creek and Swift Creek watersheds was lower, in the 8-13% range.
Stressor-Response Relationships from the Field	-2	-2	-2	-2	-2	-2	Dissolved sulfate was not significantly correlated with benthic health across sites.
Temporal Sequence	-1	-1	-1	-1	-1	-1	Sulfate levels were generally highest in the winter, which precedes lower spring benthic scores, but sulfate levels still did not exceed toxic thresholds.
Symptoms	-1	-1	-1	-1	2	-1	Biological condition gradient analysis identified the predominance of Simulium taxon in Rohoic Creek, which could be an indicator of sulfate as a stressor. In all other streams, biological condition gradient analysis ranked sulfate 5-8 out of the 10 stressors evaluated, indicating that organism tolerance patterns implicated other stressors before sulfate.
Stressor-Response Relationships from Other Field Studies	-1	-2	-3	-3	-2	-3	Average dissolved sulfate levels in all of the streams were in the no to low probability range for stressor effects. Only one anomalous value from Bailey Creek was in the high probability range.
Stressor-Response Relationships from Laboratory Studies	-1	-1	-2	-2	-2	-2	Literature thresholds for sulfate toxicity (Mount et al., 2016) were approximately 1.5 to 16 times higher than dissolved sulfate levels observed in any of the streams.

Analogous Stressors	-2	-1	-2	-2	-1	-2	Conductivity, which would increase with increasing ions, did not appear to be a primary stressor in these streams.
Multiple Types of Evidence							
Consistency of Evidence	-1	-1	-2	-2	-1	-2	Weight of evidence weakly to moderately refuted sulfate as a primary stressor.
Sum	**-10**	**-11**	**-17**	**-16**	**-9**	**-17**	

4.6. Suspended Solids and Deposited Sediment

Table 35 shows the causal analysis results for suspended solids and deposited sediment across James River Tributaries Project streams. Total causal analysis scores ranged from +4 to +19, indicating that there is moderate to strong evidence that sediment is a probable stressor in these streams. The evidence was strongest in Bailey Creek, Nuttree Branch, Oldtown Creek, Rohoic Creek, and Swift Creek (+12 to +19) and weakest in Proctors Creek (+4). This was due to several lines of evidence in Proctors Creek that refuted sediment as a cause of impairment. These included habitat scores that were higher than the reference and relative bed stability scores in the no probability range for stressor effects. Lines of evidence supporting sediment as a probable stressor in most streams included:

- Total habitat scores and habitat metrics that indicate instream sediment were significantly lower in most streams than in the reference.
- Seasonal trends in benthic health in most streams indicated poor health in the spring following high spring flows that typically bring higher sediment loads.
- Imperviousness was high in all streams, providing a causal pathway for increased runoff and instability of benthic substrate.
- Total habitat was significantly correlated with benthic health across sites.
- Biological condition gradient analysis identified predominant taxa in most streams that indicated sediment-associated stressors. Average BCG scores ranked sediment-associated stressors as the top stressors in most streams.

- Taxonomic community structure indicated shifts to Dipteran-dominated communities that prefer sediment and away from Ephemeroptera, Plecoptera, and Trichoptera, which generally prefer clean substrate.
- Functional feeding group analysis indicated shifts to filterers and collectors that prefer sediment conditions and away from shredders and scrapers that prefer clean substrate.
- Relative bed stability analysis showed that the bed substrate in some steams was unstable, consisted of a majority of sands and fines, and exhibited 53-91% embeddedness.
- High turbidity and high total suspended solids concentrations in some streams during storm events indicated transport of high sediment loads.

For these reasons and others explained in Table 35, suspended solids and deposited sediment were categorized as probable stressors.

Table 35. Causal analysis results for suspended solids and deposited sediment.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	3	2	3	-2	3	2	Total habitat scores were statistically lower than the reference in Bailey Creek, Nuttree Branch, Oldtown Creek, and Rohoic Creek. Individual habitat metrics that indicate instream sediment were statistically lower than the reference in Bailey Creek, Oldtown Creek, Rohoic Creek, and Swift Creek. Total habitat scores in Proctors Creek were higher than in the reference, and the only habitat metric statistically lower than the reference was riparian habitat.
Temporal Co-occurrence	2	2	1	0	1	0	In Bailey Creek and Nuttree Branch, the timing of the lowest habitat scores corresponded to the lowest benthic scores. In Oldtown Creek and Rohoic Creek, both habitat scores and benthic scores were consistently poor.
Causal Pathway	2	2	1	2	2	1	Bailey Creek, Nuttree Branch, Proctors Creek, and Rohoic Creek all exceeded 15% imperviousness, which means that solids on surfaces can easily runoff and increased flows can transport in-stream sediment. Imperviousness in Oldtown Creek and Swift Creek watersheds was in the 8-13% range.
Stressor-Response Relationships from the Field	3	3	3	3	3	3	Benthic habitat was the only parameter significantly correlated with benthic health across sites (p=0.04).

Temporal Sequence	1	0	0	1	1	2	Spring benthic scores were lower than fall scores in Bailey Creek, Proctors Creek, Rohoic Creek, and Swift Creek. This difference was statistically significant for Swift Creek. Lower spring scores correspond to spring high flows and sediment transport.
Symptoms	3	3	1	1	2	3	Biological condition gradient analysis identified predominant taxa in Bailey Creek, Nuttree Branch, Oldtown Creek, Rohoic Creek and Swift Creek that indicated sediment associated stressors. Average BCG scores ranked sediment associated stressors as the top stressors in Bailey Creek, Nuttree Branch, Proctors Creek, Rohoic Creek, and Swift Creek. Functional feeding group analysis showed increases in collectors that indicate sediment enrichment in Bailey Creek, Nuttree Branch, and Swift Creek.
Stressor-Response Relationships from Other Field Studies	1	1	2	-2	2	1	Total habitat scores in Bailey Creek, Oldtown Creek, and Rohoic Creek were in the medium probability range for stressor effects. Other streams were in the low probability range. Relative bed stability scores in Nuttree Branch, Oldtown Creek, Rohoic Creek, and Swift Creek were in the medium probability range for stressor effects. Other streams were in the no to low probability range.
Analogous Stressors	2	1	-1	1	-1	-1	TSS and turbidity levels in Bailey Creek were statistically higher than in the reference. Turbidity levels in Nuttree Branch and Proctors Creek during diurnal monitoring were very high. TSS and turbidity in other streams were similar to the reference.
Consistency of Evidence	2	2	2	0	2	2	Weight of evidence moderately supported sediment as a stressor in Bailey Creek, Nuttree Branch, Oldtown Creek, Rohoic Creek, and Swift Creek.
Sum	**19**	**16**	**12**	**4**	**15**	**13**	

4.7. Organic Matter

Table 36 shows the causal analysis results for organic matter across James River Tributaries Project streams. In Bailey Creek, Nuttree Branch, Rohoic Creek, and Swift Creek, total causal analysis scores ranged from -7 to -1, indicating that there is weak to moderate evidence that organic matter is a non-stressor in these streams. In Oldtown Creek and Proctors Creek, total causal analysis scores were +3, indicating that organic matter is a possible stressor in these two streams. In Oldtown Creek and Proctors Creek total organic carbon was much higher than in the reference, and dissolved organic carbon was above the 80th percentile of Mid-Atlantic coastal plain streams. High organic matter in these two streams is also consistent with observations of blackwater conditions and contributes to a causal pathway from connected wetlands to high dissolved organic matter to low pH and low DO. Additional rationale for stressor categorizations is explained in Table 36.

Table 36. Causal analysis results for organic matter.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	1	1	1	1	1	-1	Total volatile solids or total organic carbon were higher than an unimpaired reference site in all streams except for Swift Creek.
Causal Pathway	-2	-2	1	1	-2	-2	Causal pathway indicative of blackwater conditions was present for Proctors Creek and Oldtown Creek. This pathway leads from wetlands to high organic matter to low pH and low dissolved oxygen.
Stressor-Response Relationships from the Field	-2	-2	-2	-2	-2	-2	Total volatile solids was not significantly correlated with benthic health across sites.
Symptoms	0	0	1	1	1	0	An increase in filterers in Oldtown Creek, Proctors Creek, and Rohoic Creek indicate an increase in particulate organic matter.
Stressor-Response Relationships from Other Field Studies	1	1	1	1	1	-1	Total volatile solids or total organic carbon were higher than an unimpaired reference site in all streams except for Swift Creek.
Stressor-Response Relationships from Laboratory Studies	0	0	1	1	0	0	DOC in Oldtown Creek and Proctors Creek was above the 80th percentile of Mid-Atlantic coastal plain streams.
Consistency of Evidence	0	0	0	0	0	-1	Weight of evidence weakly refuted organic matter as a stressor in Swift Creek.
Sum	**-2**	**-2**	**3**	**3**	**-1**	**-7**	

4.8. Nutrients

4.8.1. Total Phosphorus

Table 37 shows the causal analysis results for total phosphorus across James River Tributaries Project streams. In Bailey Creek, Nuttree Branch, and Proctors Creek total causal analysis scores ranged from -2 to -1, indicating that there is weak evidence that phosphorus is a non-stressor in these streams. In Oldtown Creek, Rohoic Creek, and Swift Creek, total causal analysis scores ranged from +5 to +11, indicating that there is moderate to strong evidence that phosphorus is a probable stressor in these streams. Lines of evidence supporting phosphorus as a probable stressor in Oldtown Creek, Rohoic Creek, and Swift Creek included:

- Median phosphorus levels in Oldtown Creek and Rohoic Creek were in the medium probability range for stressor effects.
- Seasonal trends of lower spring benthic scores in Rohoic Creek and Swift Creek indicate possible nutrient enrichment.
- Large diurnal swings in DO in Rohoic Creek may indicate nutrient enrichment.
- Biological condition gradient analysis identified predominant taxa in Rohoic Creek and Swift Creek that indicate nutrient enrichment. Average BCG scores ranked nutrients as the top stressor in Oldtown Creek and Swift Creek.
- Functional feeding group analysis showed increases in filterers and scrapers that indicate nutrient enrichment in Oldtown Creek and Rohoic Creek.
- Streams exceeded EPA-recommended phosphorus criterion for the ecoregion.
- Chlorophyll-a and phosphorus levels in Swift Creek Reservoir exceeded DEQ nutrient criteria for lakes in 2017 and 2018, but met the criteria in 2019.

For these reasons and others explained in Table 37, phosphorus was categorized as a probable stressor in Oldtown Creek, Rohoic Creek, and Swift Creek. The remaining streams exhibited some of these characteristics, but also had lines of evidence refuting phosphorus as a stressor. As a result, phosphorus was categorized as a non-stressor in these streams.

Table 37. Causal analysis results for total phosphorus.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	-1	-1	2	-1	2	-1	In Oldtown Creek and Rohoic Creek, median phosphorus levels were in the medium probability range for stressor effects. Median phosphorus levels were in the low probability

							range in all other streams, however, all streams exceeded the EPA-recommended phosphorus criterion for the ecoregion.
Causal Pathway	0	2	0	0	2	0	Large diurnal dissolved oxygen swings in Nuttree Branch and Rohoic Creek are a link in the causal pathway between nutrients and low dissolved oxygen.
Stressor-Response Relationships from the Field	-3	-3	-3	-3	-3	-3	Total phosphorus was not significantly correlated with benthic health across sites.
Temporal Sequence	1	0	0	1	1	2	Seasonal trends of lower spring benthic scores in Bailey Creek, Proctors Creek, Rohoic Creek, and Swift Creek (statistically significant) may indicate nutrient enrichment.
Symptoms	0	0	2	1	3	3	Biological condition gradient analysis identified predominant taxa in Rohoic Creek and Swift Creek that indicated nutrient enrichment. Average BCG scores ranked total nitrogen and phosphorus as the top stressor in Oldtown Creek and Swift Creek. Functional feeding group analysis showed increases in filterers and scrapers that indicate nutrient enrichment in Oldtown Creek, Proctors Creek, and Rohoic Creek.
Stressor-Response Relationships from Other Field Studies	-2	-2	2	-2	2	-2	In Oldtown Creek and Rohoic Creek, median phosphorus levels were in the medium probability range for stressor effects. Median phosphorus levels were in the low probability range in all other streams.
Stressor-Response Relationships from Laboratory Studies	1	1	1	1	1	1	All streams exceeded the EPA-recommended phosphorus criterion for the ecoregion.
Mechanistically Plausible Cause	2	2	2	2	2	2	Nitrogen to phosphorus ratios indicate that phosphorus is the limiting nutrient in these streams.
Analogous Stressors	0	0	0	0	0	2	Chlorophyll-a and phosphorus levels in Swift Creek Reservoir exceeded DEQ nutrient criteria for lakes in 2017 and 2018, but met criteria in 2019. Nuisance algae was also a problem in the lake in 2017 and 2018.
Consistency of Evidence	0	0	1	0	1	1	Weight of evidence weakly supported phosphorus as a stressor in Oldtown Creek, Rohoic Creek, and Swift Creek.
Sum	**-2**	**-1**	**7**	**-1**	**11**	**5**	

4.8.2. Total Nitrogen

Table 38 shows the causal analysis results for total nitrogen across James River Tributaries Project streams. Total causal analysis scores ranged from -13 to -3, indicating that there is moderate to strong evidence that nitrogen is not a stressor in these streams. While some lines of evidence indicate nutrient enrichment as a stressor in some streams, nitrogen to phosphorus ratios showed that phosphorus (and not nitrogen) is the limiting nutrient. In addition, nitrogen levels were either lower than or only slightly higher than the unimpaired reference, and average nitrogen levels were in the low probability range for stressor effects. Nitrogen levels were also lower than or only slightly above EPA-recommended nutrient criteria for the ecoregion. For these reasons and others explained in Table 38, nitrogen was categorized as a non-stressor.

Table 38. Causal analysis results for total nitrogen.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	-3	-3	-3	-2	-2	-3	No streams were statistically higher in total nitrogen than the reference. Bailey Creek, Nuttree Branch, Oldtown Creek, and Swift Creek were lower than the reference. Average nitrogen in all streams was in the low probability range for stressor effects.
Causal Pathway	0	2	2	1	2	2	Low DO in Oldtown Creek, Proctors Creek, and Swift Creek and large daily DO swings in Nuttree Branch and Swift Creek indicate that nutrient enrichment pathways are intact.
Stressor-Response Relationships from the Field	-3	-3	-3	-3	-3	-3	Total nitrogen was not significantly correlated with benthic health across sites.
Temporal Sequence	1	0	0	1	1	2	Seasonal trends of lower spring benthic scores in Bailey Creek, Proctors Creek, Rohoic Creek, and Swift Creek (statistically significant) may indicate nutrient enrichment.
Symptoms	1	1	2	2	3	3	Biological condition gradient analysis identified predominant taxa in Rohoic Creek and Swift Creek that indicated nutrient enrichment. Average BCG scores ranked total nitrogen and phosphorus as the top stressor in Oldtown Creek and Swift Creek and second stressor in Bailey Creek, Nuttree Branch, and Rohoic Creek. Functional feeding group analysis showed increases in filterers and scrapers that indicate nutrient enrichment in Oldtown Creek, Proctors Creek, and Rohoic Creek.
Stressor-Response Relationships from Other Field Studies	-3	-3	-3	-2	-2	-3	No streams were statistically higher in total nitrogen than the reference. Bailey Creek, Nuttree Branch, Oldtown Creek, and Swift Creek were lower than the reference. Average nitrogen in all streams was in the low probability range for stressor effects.
Stressor-Response Relationships from Laboratory Studies	-2	1	1	1	1	-2	Median nitrogen levels in Bailey Creek and Swift Creek were below the EPA-recommended nutrient criterion for the ecoregion. Other streams were slightly above the criterion.
Mechanistically Plausible Cause	-3	-3	-3	-3	-3	-3	Nitrogen to phosphorus ratios indicate that phosphorus (and not nitrogen) is the limiting nutrient in these streams.

Consistency of Evidence	-1	-1	-1	0	0	-1	Weight of evidence weakly refuted nitrogen as a stressor in Bailey Creek, Nuttree Branch, Oldtown Creek, and Swift Creek.
Sum	**-13**	**-9**	**-8**	**-5**	**-3**	**-8**	

4.9. Ammonia

Table 39 shows the causal analysis results for ammonia across James River Tributaries Project streams. Total causal analysis scores ranged from -20 to -19, indicating that there is strong evidence that ammonia is not a stressor in these streams. All samples in all streams were well below the water quality standard for ammonia. Based on multiple lines of evidence explained in Table 39, ammonia was categorized as a non-stressor in all James River Tributaries Project streams.

Table 39. Causal analysis results for ammonia.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	-3	-3	-3	-3	-3	-3	Ammonia levels were well below the respective water quality standard for all samples in all streams.
Temporal Co-occurrence	-3	-3	-3	-3	-3	-3	High ammonia values were not observed at the time of impaired benthic sampling.
Causal Pathway	-3	-3	-3	-3	-3	-3	Ammonia is more toxic at higher pH and all sites had neutral to acidic pH, making ammonia toxicity very unlikely.
Stressor-Response Relationships from the Field	-3	-3	-3	-3	-3	-3	Ammonia was not significantly correlated with benthic health across sites.
Temporal Sequence	-2	-1	-1	-2	-2	-2	Ammonia levels are generally highest in the late summer when water temperatures are highest. Yet Bailey Creek, Proctors Creek, Rohoic Creek, and Swift Creek exhibited higher fall benthic scores (following hot summer months) than spring scores. Benthic scores were consistent between fall and spring in Nuttree Branch and Oldtown Creek.
Symptoms	0	0	0	0	0	0	None of the streams exhibited symptoms that would specifically indicate ammonia as a primary stressor. All streams exhibited a lack of richness of sensitive species (EPT taxa), but this could indicate almost any physical or chemical stressor. Biological condition gradient analysis indicated a

							combination of sediment and nutrient enrichment as the highest ranked stressors.
Stressor-Response Relationships from Other Field Studies	0	0	0	0	0	0	Only one sample from the reference site was available, so reference comparisons could not be made. Benthic stressor probability thresholds were also not available for ammonia.
Stressor-Response Relationships from Laboratory Studies	-3	-3	-3	-3	-3	-3	Ammonia levels were well below the respective water quality standard for all samples in all streams.
Consistency of Evidence	-3	-3	-3	-3	-3	-3	Weight of evidence strongly refuted ammonia as a primary stressor.
Sum	**-20**	**-19**	**-19**	**-20**	**-20**	**-20**	

4.10. Dissolved Metals

Table 40 shows the causal analysis results for dissolved metals across James River Tributaries Project streams. Total causal analysis scores ranged from -13 to -3, indicating that there is moderate to strong evidence that dissolved metals are not a stressor in these streams. In all streams, the CCU was in the no to low probability range for stressor effects. All metals in all streams (except for Se in Rohoic Creek) were below water quality standards and reference toxicity values. Sediment metals were also below probable effect concentrations in all streams. For these reasons and others explained in Table 40, dissolved metals were categorized as non-stressors in all James River Tributaries Project streams.

Table 40. Causal analysis results for dissolved metals.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	-3	-3	-3	-3	1	-3	Dissolved metals in all streams (except for Rohoic Creek) were below WQSs and TRVs. In Rohoic Creek Se exceeded the WQS on one occasion. The CCU in all streams was in the no to low probability range for stressor effects.
Stressor-Response Relationships from Other Field Studies	-3	-3	-3	-3	-3	-3	The CCU in all streams was in the no to low probability range for stressor effects.
Stressor-Response Relationships from Laboratory Studies	-3	-3	-3	-3	1	-3	Dissolved metals in all streams (except for Rohoic Creek) were below WQSs and TRVs. In Rohoic Creek Se exceeded the WQS on one occasion.

Analogous Stressors	0	-2	-2	0	-2	2	In Swift Creek, sediment metals were above TECs but below PECs. All sediment metals were below TECs in Nuttree Branch, Oldtown Creek, and Rohoic Creek. No sediment metals data were available for Bailey Creek or Proctors Creek.
Consistency of Evidence	-1	-2	-2	-2	0	-1	Weight of evidence moderately refuted dissolved metals as a stressor in Nuttree Branch, Oldtown Creek, and Proctors Creek and weakly refuted dissolved metals as a stressor in Bailey Creek and Swift Creek.
Sum	**-10**	**-13**	**-13**	**-11**	**-3**	**-8**	

4.11. Sediment Metals

Table 41 shows the causal analysis results for sediment metals across James River Tributaries Project streams. Total causal analysis scores ranged from -7 to +1. In Bailey Creek, Nuttree Branch, Oldtown Creek, Proctors Creek, and Rohoic Creek, all sediment metals (or water column metals) were below toxic thresholds. For this reason, and others explained in Table 41, sediment metals were categorized as a non-stressor in these streams. In Swift Creek, sediment metals were categorized as a possible stressor. Levels of Cu and Pb in Swift Creek sediments were above threshold effect concentrations (TECs) but below probable effect concentrations (PECs). Additional rationale for stressor categorizations is explained in Table 41.

Table 41. Causal analysis results for sediment metals.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	0	-2	-2	0	-2	1	In Swift Creek, Cu and Pb were above TECs but below PECs. All sediment metals were below TECs in Nuttree Branch, Oldtown Creek, and Rohoic Creek. No sediment metals data were available for Bailey Creek or Proctors Creek.
Causal Pathway	0	0	0	0	0	1	In Swift Creek Reservoir, copper sulfate is added for algae control.
Stressor-Response Relationships from Laboratory Studies	0	-2	-2	0	-2	1	In Swift Creek, Cu and Pb were above TECs but below PECs. All sediment metals were below TECs in Nuttree Branch, Oldtown Creek, and Rohoic Creek. No sediment metals data were available for Bailey Creek or Proctors Creek.

Analogous Stressors	-2	-2	-2	-2	1	-2	In all streams (except Rohoic Creek), levels of dissolved metals were below WQS and toxic thresholds. In Rohoic Creek, Se exceeded the WQS.
Consistency of Evidence	0	-1	-1	0	0	0	Weight of evidence weakly refuted sediment metals as a stressor in Nuttree Branch and Oldtown Creek.
Sum	**-2**	**-7**	**-7**	**-2**	**-3**	**1**	

4.12. Polycyclic Aromatic Hydrocarbons (PAHs)

Table 42 shows the causal analysis results for PAHs across James River Tributaries Project streams. Total causal analysis scores ranged from -5 to 0, indicating that there is weak to moderate evidence in some streams that PAHs are not a stressor. PAHs in water were less than detection in Swift Creek, and PAHs in sediment were below probable effect concentrations in Bailey Creek. PAHs were not measured in Nuttree Branch, but high levels would likely be captured in downstream Swift Creek monitoring. The remaining streams had no PAH data, so causal analysis scores were 0. Based on the rationale explained in Table 42, PAHs were categorized as a non-stressor in Bailey Creek, Nuttree Branch, and Swift Creek. PAHs were categorized as indeterminate in the remaining streams due to insufficient data.

Table 42. Causal analysis results for PAHs.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	-2	-1	0	0	0	-2	PAHs were measured on one occasion in water in Swift Creek, and all 16 PAHs were below detection limits. PAHs were measured in sediments in Bailey Creek on one occasion, and all 24 PAHs were below PECs. PAHs were not measured in other streams, but PAHs are unlikely in Nuttree Branch, because they would have been captured in downstream Swift Creek monitoring.
Stressor-Response Relationships from Laboratory Studies	-2	-1	0	0	0	-2	PAHs were measured on one occasion in water in Swift Creek, and all 16 PAHs were below detection limits. PAHs were measured in sediments in Bailey Creek on one occasion, and all 24 PAHs were below PECs. PAHs were not measured in other streams, but PAHs are unlikely in Nuttree Branch, because they would have been captured in downstream Swift Creek monitoring.

Consistency of Evidence	-1	0	0	0	0	-1	Weight of evidence weakly refuted PAHs as a stressor in Bailey Creek and Swift Creek.
Sum	**-5**	**-2**	**0**	**0**	**0**	**-5**	

4.13. Polychlorinated Biphenyls (PCBs)

Table 43 shows the causal analysis results for PCBs across James River Tributaries Project streams. In Nuttree Branch, Oldtown Creek, and Swift Creek, total causal analysis scores ranged from -9 to -3, indicating that there is weak to moderate evidence that PCBs are not a stressor in these streams. PCBs were below detection in Oldtown Creek and Swift Creek, and while PCBs were not measured in Nuttree Branch, there presence is unlikely, because they would have been captured in downstream Swift Creek monitoring. In Bailey Creek, the total causal analysis score was +3, indicating that PCBs are a possible stressor. Near the mouth of Bailey Creek, significant PCB contamination is present. Sources have been identified, and these sources will be addressed through the James River TMDL. At the upstream Bailey Creek benthic monitoring station, PCB levels are low and no sources have been identified, however, fish collected at these upstream locations have exceeded DEQ screening criteria for PCBs. This could result from upstream movement of fish from more contaminated areas, but it may also point to more local PCB sources. For this reason, and other explained in Table 43, PCBs were categorized as a possible stressor in Bailey Creek. In Proctors Creek and Rohoic Creek, PCBs were categorized as indeterminate due to insufficient data.

Table 43. Causal analysis results for PCBs.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	1	-1	-3	0	0	-3	PCBs were detected in high concentrations above screening levels in water and sediment at downstream tidal locations in Bailey Creek, but not at the benthic location. PCBs were below detection in Oldtown Creek and Swift Creek. PCBs are not likely in Nuttree Branch, because they were not detected downstream in Swift Creek. No data were available for Proctors Creek and Rohoic Creek.

Causal Pathway	1	0	0	0	0	0	PCB sources have been identified in the Bailey Creek watershed, but those sources are downstream from the benthic site.
Symptoms	2	0	0	0	0	0	PCBs were detected in fish above screening levels at the Bailey Creek impaired benthic station.
Stressor-Response Relationships from Laboratory Studies	1	-1	-3	0	0	-3	PCBs were detected in high concentrations above screening levels in water and sediment at downstream tidal locations in Bailey Creek, but not at the benthic location. PCBs were below detection in Oldtown Creek and Swift Creek. PCBs are not likely in Nuttree Branch, because they were not detected downstream in Swift Creek. No data were available for Proctors Creek and Rohoic Creek.
Mechanistically Plausible Cause	-2	0	0	0	0	0	Known PCB sources are downstream from the impaired benthic station.
Consistency of Evidence	0	-1	-3	0	0	-3	Limited evidence is ambiguous in Bailey Creek but weakly refutes PCBs as a stressor in Nuttree Branch and strongly refutes PCBs as a stressor in Swift Creek and Oldtown Creek.
Sum	**3**	**-3**	**-9**	**0**	**0**	**-9**	

4.14. Pesticides

Table 44 shows the causal analysis results for pesticides across James River Tributaries Project streams. Total causal analysis scores ranged from -8 to 0, indicating that there is weak to moderate evidence in some streams that pesticides are not a stressor. Pesticides were less than detection in Bailey Creek, Oldtown Creek, and Swift Creek. Pesticides were not measured in Nuttree Branch, but high levels would likely be captured in downstream Swift Creek monitoring. The remaining streams had no pesticide data, so causal analysis scores were 0. Based on the rationale explained in Table 44, pesticides were categorized as a non-stressor in Bailey Creek, Nuttree Branch, and Swift Creek. Pesticides were categorized as indeterminate in the remaining streams due to insufficient data.

Table 44. Causal analysis results for pesticides.

Evidence	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek	Explanation
Spatial Co-occurrence	-1	-1	-2	0	0	-3	Pesticides were analyzed in sediments on 1 occasion in Bailey Creek and Oldtown Creek and on 3 occasions in Swift Creek.

							All measured pesticides were below detection limits. No data on pesticides was available for Nuttree Branch, Proctors Creek, or Rohoic Creek, but pesticides are not likely a stressor in Nuttree Branch, because they would have been detected in downstream Swift Creek monitoring.
Symptoms	2	0	0	0	0	0	Pesticides were detected in fish above screening levels at the Bailey Creek impaired benthic station.
Stressor-Response Relationships from Laboratory Studies	-1	-1	-2	0	0	-3	Pesticides were analyzed in sediments on 1 occasion in Bailey Creek and Oldtown Creek and on 3 occasions in Swift Creek. All measured pesticides were below detection limits. No data on pesticides was available for Nuttree Branch, Proctors Creek, or Rohoic Creek, but pesticides are not likely a stressor in Nuttree Branch, because they would have been detected in downstream Swift Creek monitoring.
Consistency of Evidence	0	-1	-1	0	0	-2	Weight of evidence weakly refuted pesticides as a stressor in Nuttree Branch and Oldtown Creek and moderately refuted pesticides as a stressor in Swift Creek.
Sum	**0**	**-3**	**-5**	**0**	**0**	**-8**	

5.0 CAUSAL ANALYSIS SUMMARY

5.1. Probable Stressors

The total causal analysis scores for each candidate stressor are shown in Table 45. Candidate stressors with causal analysis scores ≤0 were classified as non-stressors, candidate stressors with causal analysis scores of 1-3 were classified as possible stressors, and candidate stressors with scores >3 were classified as probable stressors. If no data were available for a candidate stressor in a particular stream, that candidate stressor was classified as indeterminant. Table 46 shows the non-stressors, possible stressors, and probable stressors identified for each impaired stream. The results indicate that sediment was identified as a probable stressor in all of the James River Tributaries Project streams, with causal analysis scores ranging from +4 to +19. In addition, phosphorus, was identified as a probable stressor in Oldtown Creek, Rohoic Creek, and Swift Creek, with causal analysis scores ranging from +5 to +11. Dissolved oxygen was a probable stressor in Oldtown Creek and Swift Creek, with causal analysis scores of +7 and +11, respectively. pH was a probable stressor in Oldtown Creek and Proctors Creek, with causal analysis scores of +11 and +12, respectively.

Table 45. Total causal analysis scores by stream and by candidate stressor. Green indicates non-stressors, orange indicates possible stressors, red indicates probable stressors, and white indicates indeterminant.

Candidate Stressor	Bailey Creek	Nuttree Branch	Oldtown Creek	Proctors Creek	Rohoic Creek	Swift Creek
Ammonia	-20	-19	-19	-20	-20	-20
Conductivity	-23	-16	-24	-23	-13	-24
Dissolved Chloride	-16	-7	-16	-16	1	-17
Dissolved Metals	-8	-13	-13	-11	-3	-8
Dissolved Oxygen	-1	2	7	3	1	11
Dissolved Potassium	-9	-8	-9	-11	-8	-10
Dissolved Sodium	-8	1	-8	-8	-3	-16
Dissolved Sulfate	-10	-11	-17	-16	-9	-17
Nitrogen	-13	-9	-8	-5	-3	-8
Organic Matter	-2	-2	3	3	-1	-7
PAHs	-5	-2	0	0	0	-5
PCBs	3	-3	-9	0	0	-9
Pesticides	0	-3	-5	0	0	-8
pH	-22	-31	11	12	-31	-31
Phosphorus	-2	-1	7	-1	11	5
Sediment	19	16	12	4	15	13
Sediment Metals	-2	-7	-7	-2	-3	1
Temperature	-20	-17	-17	-18	-17	-16

Table 46. Non-stressors, possible stressors, and probable stressors in James River Tributaries Project streams.

Stream	Non-Stressors	Possible Stressors	Probable Stressors	TMDL Target
Bailey Creek	Ammonia, Conductivity, Dissolved Chloride, Dissolved Metals, Dissolved Oxygen, Dissolved Potassium, Dissolved Sodium, Dissolved Sulfate, Nitrogen, Organic Matter, PAHs, Pesticides, pH, Phosphorus, and Temperature	-PCBs	-Sediment	-Sediment
Nuttree Branch	Ammonia, Conductivity, Dissolved Chloride, Dissolved Metals, Dissolved Potassium, Dissolved Sulfate, Nitrogen, Organic Matter, PAHs, PCBs, Pesticides, pH, Phosphorus, Sediment Metals, and Temperature	-Dissolved Oxygen -Dissolved Sodium	-Sediment	-Sediment
Oldtown Creek	Ammonia, Conductivity, Dissolved Chloride, Dissolved Metals, Dissolved	-Organic Matter	-Dissolved Oxygen -pH	-Phosphorus -Sediment

	Potassium, Dissolved Sodium, Dissolved Sulfate, Nitrogen, PAHs, PCBs, Pesticides, Sediment Metals, and Temperature		-Phosphorus -Sediment	
Proctors Creek	Ammonia, Conductivity, Dissolved Chloride, Dissolved Metals, Dissolved Potassium, Dissolved Sodium, Dissolved Sulfate, Nitrogen, PAHs, PCBs, Pesticides, Phosphorus, Sediment Metals, and Temperature	-Dissolved Oxygen -Organic Matter	-pH -Sediment	-Sediment
Rohoic Creek	Ammonia, Conductivity, Dissolved Metals, Dissolved Oxygen, Dissolved Potassium, Dissolved Sodium, Dissolved Sulfate, Nitrogen, Organic Matter, PAHs, PCBs, Pesticides, pH, Sediment Metals, and Temperature	-Dissolved Chloride -Dissolved Oxygen	-Phosphorus -Sediment	-Phosphorus -Sediment
Swift Creek	Ammonia, Conductivity, Dissolved Chloride, Dissolved Metals, Dissolved Potassium, Dissolved Sodium, Dissolved Sulfate, Nitrogen, Organic Matter, PAHs, PCBs, Pesticides, pH, and Temperature	-Sediment Metals	-Dissolved Oxygen -Phosphorus -Sediment	-Phosphorus -Sediment

5.1.1. Sediment

Sediment was identified as a probable stressor in all of the James River Tributaries Project streams. Multiple lines of evidence supported this determination including habitat metrics, relative bed stability measurements, seasonal trends, biological condition gradient analysis, taxonomic community structure, and functional feeding group analysis (Section 4.6). Based on the observed data and causal analysis, a conceptual model was developed to describe the causal relationships between the sources of sediment in the watershed, increased suspended sediment loads, and the observed loss of benthic macroinvertebrates (Figure 40). In this conceptual model, sources of sediment are derived from the erosion of watershed soils, the washoff of accumulated sediment on impervious surfaces, the erosion of streambanks, and the resuspension of channel sediments. These sources and other contributing factors lead to an increased particulate load (i.e., suspended sediment) in the stream. The increased particulate load then acts to biologically impair the stream through two pathways: a change in feeding niches to favor filter feeders and deposit feeders, and the filling of interstitial spaces that reduces available habitat. Benthic taxa data provide evidence of these pathways with an observed increase in filter and deposit feeders and a decrease in taxa richness. Habitat assessments and relative bed stability analysis also provide evidence of interstitial filling. The combined weight of evidence documented in the causal analysis supports this conceptual model of sediment as a stressor in the James River Tributaries Project streams. A TMDL developed to reduce sediment loads in the watershed will address the benthic impairments in these streams through the pathways described in Figure 40. In addition, efforts to address several contributing factors that exacerbate the impact of the sediment stressor will also be effective at reducing the impairment.

5.1.1.1. Contributing Factors

Several factors contribute to the impact of sediment in James River Tributaries streams, including the naturally low slope and underlying geology of streams in the region, land disturbance, high percent imperviousness in the watersheds, and poor riparian vegetation. Many of the streams in this region have naturally low slopes, ranging from 0.0002 to 0.0016 ft/ft. This increases the deposition of transported sediment in these streams. In addition, the underlying geology of the Triassic Basin naturally produces sandy stream bottoms of often unconsolidated material that is very mobile. This creates reduced habitat conditions for benthic macroinvertebrates that require more stable benthic substrate.

Land disturbance from development is another contributing factor to sediment impairment in the James River Tributaries Project streams. Land disturbance greatly increases the rates of watershed erosion, and while land disturbance is addressed in the TMDL through general permits, other actions can reduce the impact of this contributing factor. This includes proper enforcement of erosion and sediment control practices and regional planning and zoning practices that protect stream corridors.

Imperviousness is a significant factor contributing to sediment impairment in the James River Tributaries Project streams. As watersheds develop and the percentage of impervious surfaces increases, runoff during precipitation events increases. As the amount of runoff increases, peak flows in local streams increase causing streambank erosion and stream bed scouring. This scenario causes unstable habitat conditions for benthic macroinvertebrates and increased sediment loads. Brabec *et al.* (2002), found that fish and macroinvertebrate diversity decreased when watersheds exceeded 3.6 to 15% imperviousness, and James River Tributaries Project streams range from 8%

to 28% impervious. While the TMDL does not directly address the percentage of imperviousness in watersheds, efforts to reduce imperviousness and increase infiltration can support the TMDL and assist in reducing the impact of sediment. Practices such as rain gardens, green roofs, rain barrels, and pervious pavers can all reduce runoff. Regional planning, zoning practices, and building codes can also be implemented to discourage imperviousness and reduce runoff.

Lastly, poor riparian vegetation is a contributing factor to sediment impairments in James River Tributaries Project streams. Riparian vegetation stabilizes stream banks and reduces bank erosion, which can often be a primary contributor to in-stream sediment loads. Practices such as riparian plantings, greenways, conservation easements, and regional planning and zoning practices that protect stream corridors can be effective mechanisms for reducing sediment loads from streambank erosion.

5.1.2. Phosphorus and Dissolved Oxygen

Phosphorus was identified as a probable stressor in Oldtown Creek, Rohoic Creek, and Swift Creek, and dissolved oxygen was a probable stressor in Oldtown Creek and Swift Creek. Multiple lines of evidence supported this determination including periodic phosphorus and DO measurements, diurnal monitoring, seasonal trends, biological condition gradient analysis, functional feeding group analysis and Swift Creek Reservoir water quality assessments (Section 4.8.1 and 4.3). Based on the observed data and causal analysis, a conceptual model was developed to describe the causal relationships between the sources of phosphorus in the watershed, increased nutrient loads, decreased DO, and the observed loss of benthic macroinvertebrates (Figure 41). In this conceptual model, sources of phosphorus include runoff of fertilizers and other diffuse sources, point sources, exfiltration and overflows from sewer systems, and failure of septic systems. These sources and other contributing factors lead to increased nutrient load in the stream, which can act to biologically impair the stream through two pathways. Increased nutrient availability increases algae growth, which can directly alter macroinvertebrate feeding niches and competition or indirectly limit sensitive species through oxygen decreases as algae respire or are decomposed. Benthic taxa data provide evidence of these pathways with an observed increase in filterers and scrapers and a decrease in taxa richness. Large DO swings in diurnal DO monitoring also provided evidence of these pathways. The combined weight of evidence documented in the causal analysis supports this conceptual model of phosphorus as a stressor in Oldtown Creek, Rohoic Creek, and Swift Creek. A TMDL developed to reduce phosphorus loads in the watershed will address the benthic impairments in these streams through the pathways described in Figure 41. In addition, efforts to address several contributing factors that exacerbate the impact of nutrient enrichment will also be effective at reducing the impairment.

5.1.2.1. Contributing Factors

Several factors contribute to the impact of nutrient enrichment and low dissolved oxygen in Oldtown Creek, Rohoic Creek, and Swift Creek. In each stream, high imperviousness, aging sewer systems, and stormwater inflow and infiltration increase the sources and movement of phosphorus. Impervious areas provide direct conduits for diffuse nutrient sources to be quickly transported to streams through storm sewer networks. For instance, pet waste or fertilizers inadvertently applied to impervious surfaces can wash directly into streams with any chance for retention and uptake from soils. In addition, sewer systems that are aging and susceptible to inflow and infiltration of stormwater can provide routes for exfiltration during dry periods and increase the likelihood of sewer overflows during wet periods. Practices and programs to reduce stormwater inflow and infiltration can reduce nutrient loads and protect human health from sanitary sewer overflows.

Several contributing factors were also specific to individual streams. In Rohoic Creek, poor riparian vegetation, which is also a contributing factor for the sediment stressor, increases the amount of sunlight that hit the stream. In the presence of ample nutrients, increased sunlight can spur algal growth and exacerbate nutrient enrichment problems. In Swift Creek, the naturally low slope and the presence of lakes and impoundments are contributing factors that increase the impact of nutrient enrichment and independently lower dissolved oxygen. These factors decrease velocity and increase depth, which decreases oxygen reaeration and overall dissolved oxygen levels. In addition, the impoundments increase water temperature and increase residence time, which increases nutrient cycling and the production of algae. It is likely that these contributing factors in Swift Creek are larger drivers of dissolved oxygen impairment than nutrient loads alone. In the stream segment just below the Swift Creek Reservoir dam, dissolved oxygen conditions may be particularly impacted by the reservoir. During the summer, the lake stratifies and the deeper hypolimnetic portions of the lake decrease in oxygen. These low dissolved oxygen hypolimnetic waters could impact downstream water quality when the lake level is below the spillway and seepage from the dam constitutes the majority of downstream flow. VDEQ plans to further investigate this contributing factor to low dissolved oxygen in Swift Creek (see Section 5.3).

5.1.3. pH and Dissolved Oxygen

Low pH was identified as a probable stressor in Oldtown Creek and Proctors Creek, and low dissolved oxygen was a probable stressor in Oldtown Creek. Multiple lines of evidence supported this determination including periodic pH measurements, diurnal pH and DO monitoring, taxonomic community structure, and causal pathway analysis (Section 4.2). Based on the observed data and causal analysis, a conceptual model was developed to describe the causal relationships between the presence of connected wetlands in these watersheds, anaerobic decomposition, high organic matter, low pH, low DO, and the observed loss of benthic macroinvertebrates (Figure 42). In this conceptual model, the low pH in Oldtown Creek and Proctors Creek results from these streams' natural connection to low-lying wetlands. In these permanently or periodically flooded wetlands, oxygen is quickly depleted and decomposition of dense organic matter proceeds through alternative anaerobic pathways that can produce organic acids and hydrogen ions, lowering the pH when wetlands are flushed during precipitation events. The low pH can be toxic to some sensitive macroinvertebrates and limit the diversity of the benthic community. In addition to low dissolved oxygen conditions in Oldtown Creek resulting from nutrient enrichment (Section 5.1.2), flushing of dissolved organic matter from connected wetlands can also provide microbes with a constant source of organic matter, and decomposition can further lower dissolved oxygen. Because the low pH in these streams is a natural condition resulting from the prevalence of connected wetlands, no TMDL will be developed to address pH specifically. The low dissolved oxygen stressor in Oldtown Creek will be addressed through a phosphorus TMDL (Section 5.1.2).

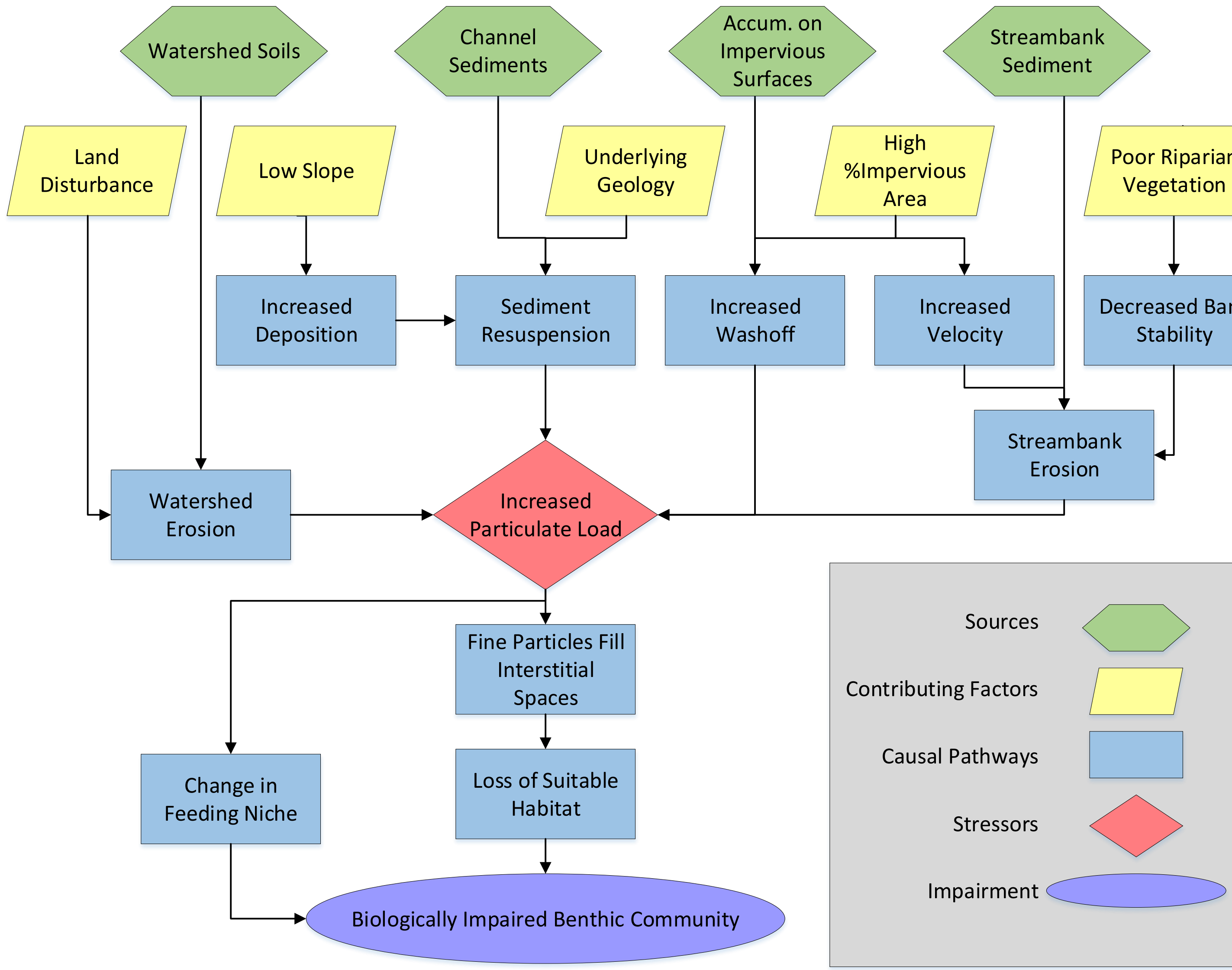

Figure 40. Conceptual model for the causal pathway of sediment impacts on benthic macroinvertebrates in James River Tributaries Project streams.

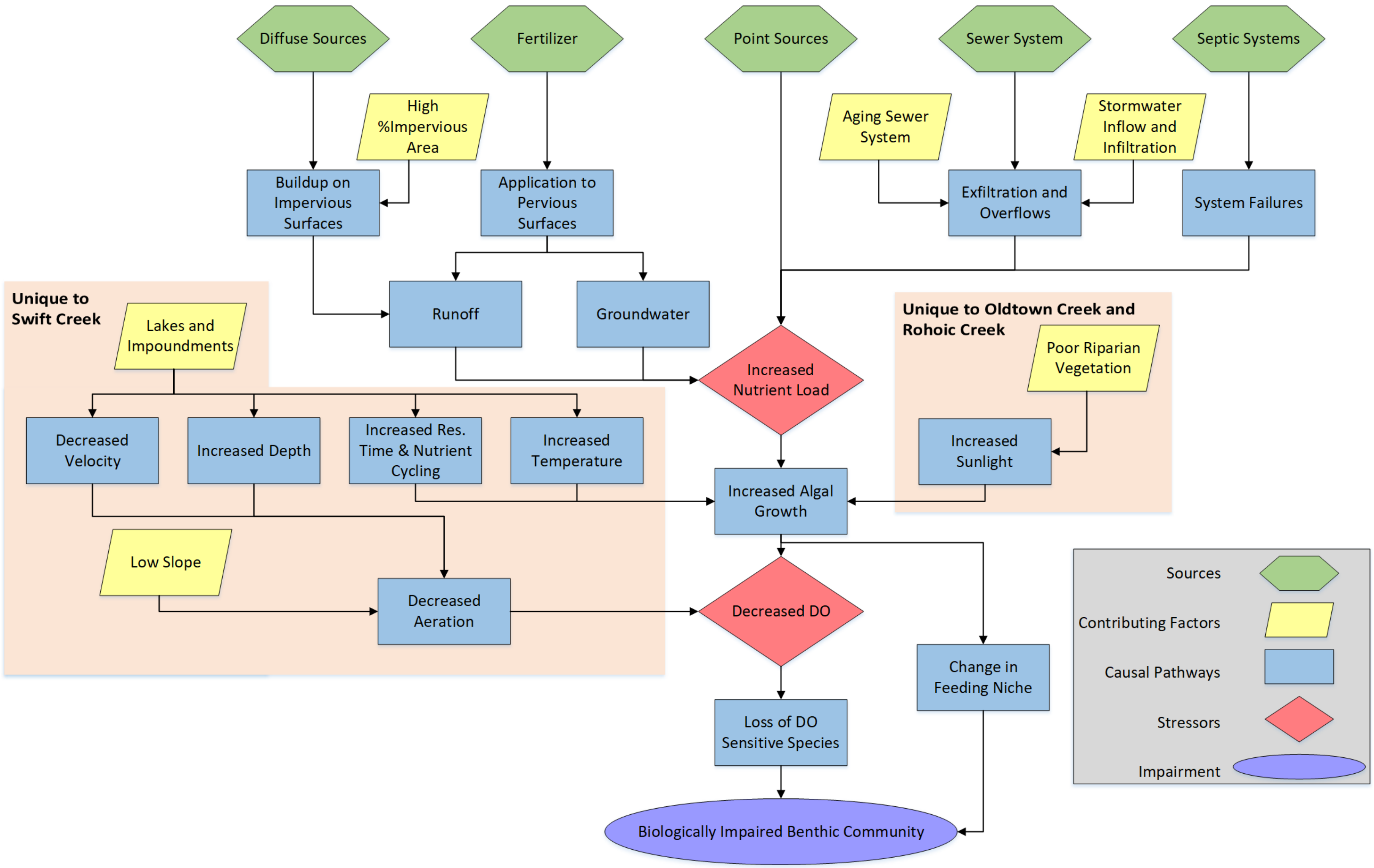

Figure 41. Conceptual model for the causal pathway of nutrient and dissolved oxygen impacts on benthic macroinvertebrates in Oldtown Creek, Rohoic Creek, and Swift Creek.

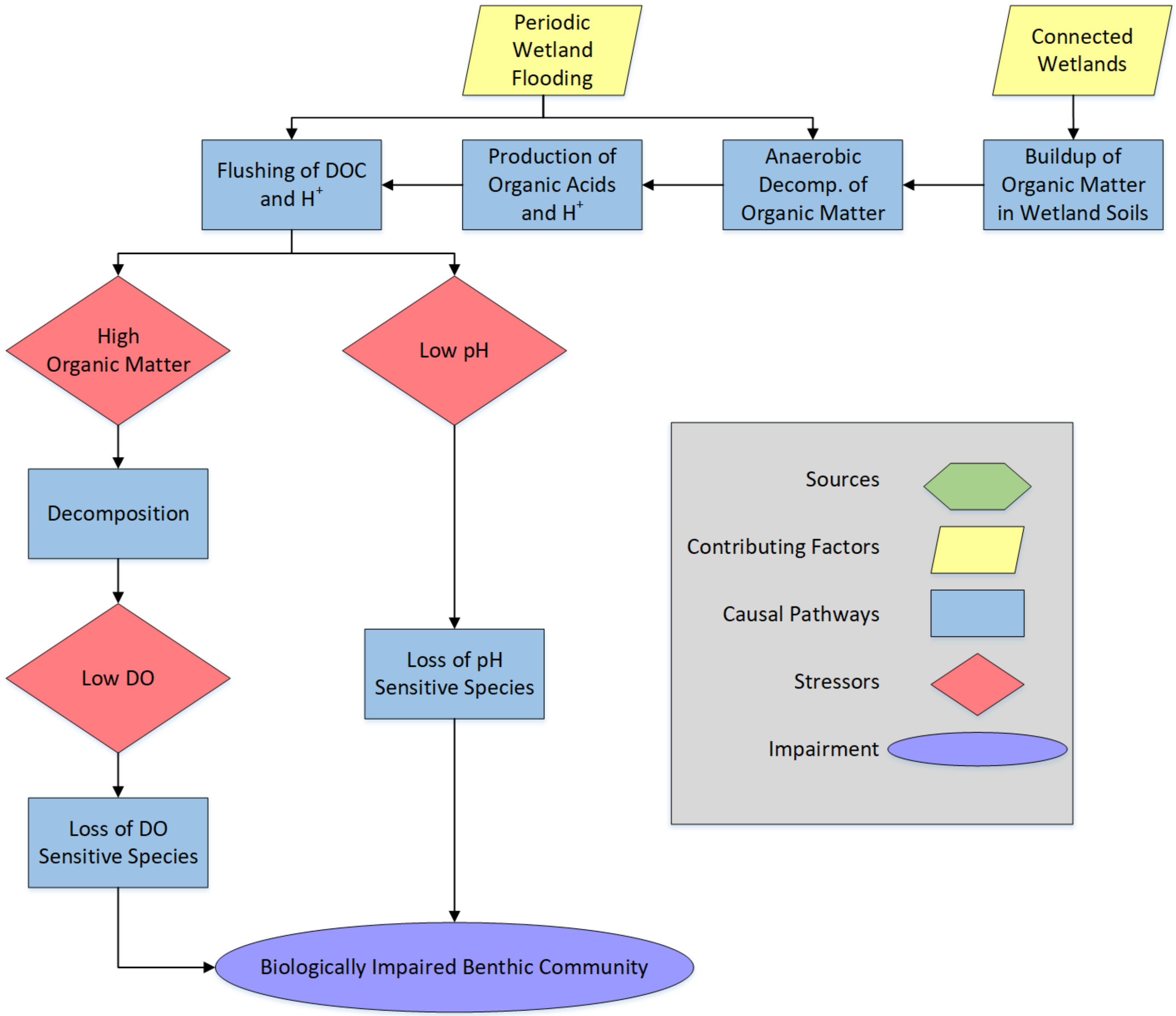

Figure 42. Conceptual model for the causal pathway of organic matter, pH, and DO impacts on benthic macroinvertebrates in Oldtown Creek and Proctors Creek.

5.2. Conclusions

Following causal analysis and the determination of probable stressors, target pollutants for the TMDL were selected. TMDL target pollutants are the physical or chemical substances that will be controlled and allocated in the TMDL to result in restored aquatic life (measured by benthic macroinvertebrate health). TMDL targets must be pollutants that are controllable through source reductions, such as sediment, phosphorus, nitrogen, or other substances. Physical factors or environmental conditions, such as flow regimes, hydrologic modifications, or physical structures (like dams) cannot be TMDL target pollutants. Even though these conditions influence ecological communities and may be sources of stress, they do not represent substances that originate from point and nonpoint sources, they cannot be quantified, summed, and allocated to respective sources, and they cannot be controlled through source reductions. Other stressors and contributing factors that are natural, such as the low pH condition in Oldtown Creek and Proctors Creek or the low slope in several James River Tributaries Project streams, also cannot be the target of TMDL development, because there is no controllable anthropogenic source.

TMDL target pollutants were selected by analyzing the causal pathways of probable stressors and identifying the primary substance responsible for controlling the pathway. For Bailey Creek, Nuttree Branch, Oldtown Creek, Proctors Creek, Rohoic Creek, and Swift Creek, the TMDL target pollutant was sediment. For Oldtown Creek, Rohoic Creek, and Swift Creek, a second TMDL target pollutant of phosphorus was also identified (Table 47).

Table 47. TMDL targets for each impaired stream.

Stream	TMDL Target
Bailey Creek	Sediment
Nuttree Branch	Sediment
Oldtown Creek	Phosphorus Sediment
Proctors Creek	Sediment
Rohoic Creek	Phosphorus Sediment
Swift Creek	Phosphorus Sediment

5.3. Associated DO Impairment in Swift Creek

In addition to the benthic impairment in Swift Creek, a 3.78 mile portion of Swift Creek from the Swift Creek Reservoir dam downstream to the confluence with Reedy Creek (Assessment Unit VAP-J17R_SFT01A00) is also listed on the 2020 Water Quality Assessment Report (VDEQ, 2020) as impaired for dissolved oxygen (Cause Group Code: J17R-08-DO). In Section 5.1.2.1 above, the presence of the dam and impoundment were listed as contributing factors to the dissolved oxygen and phosphorus stressors in Swift Creek. While the phosphorus stressor plays a role throughout the watershed, the dam may play a distinct role in low dissolved oxygen in the stream segment directly downstream from the dam (Assessment Unit VAP-J17R_SFT01A00). TMDL efforts to reduce phosphorus loadings to the watershed could improve dissolved oxygen conditions and benthic health throughout the Swift Creek watershed, but if low dissolved oxygen from the hypolimnion of the lake constitutes a significant portion of downstream flow during dry periods, dissolved oxygen conditions directly downstream from the dam may not improve with the implementation of phosphorus TMDL efforts.

VDEQ plans to conduct additional monitoring below the dam during normal and low flow periods to evaluate the influence of the dam on dissolved oxygen. If this monitoring demonstrates that low DO conditions downstream from the dam are caused by either naturally occurring conditions or the dam on Swift Creek Reservoir, VDEQ would likely pursue a Category 4C Assessment (impaired but not needing a TMDL) for the 3.78-mile stream segment directly downstream from the dam.

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